

Structural UT: Variables Affecting Attenuation and Review of the 2 dB per Inch Model

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Purpose & Practical Applications

The North American standards for welded steel construction, CSA W59^[1] and AWS D1.1^[2], use an approximation for ultrasonic attenuation of 2dB/in. This approximation is based on the use of large, low frequency transducers which are not always well-suited to the wide range of weld thicknesses and geometries used in the codes. This paper documents computer simulations and experimental results performed to gauge the suitability of this linear factor to approximate a non-linear phenomenon.

Additionally, models of smaller transducers and higher frequencies are included to study their effect. This is performed to determine how alternate criteria and procedures may be developed to retain the same levels of sensitivity but expand the range of transducers beyond that currently permitted.

Background

Instructions exist in CSA W59 and AWS D1.1 to establish the reference level based on the response from a target commonly available to all UT operators. The target is the 1.5 mm diameter side-drilled hole (SDH) located 15 mm below the test surface of the IIW-Type block (see **Figure 1**). This is referred to as the “standard reference reflector”.

The response from this target is then set to a procedurally defined screen

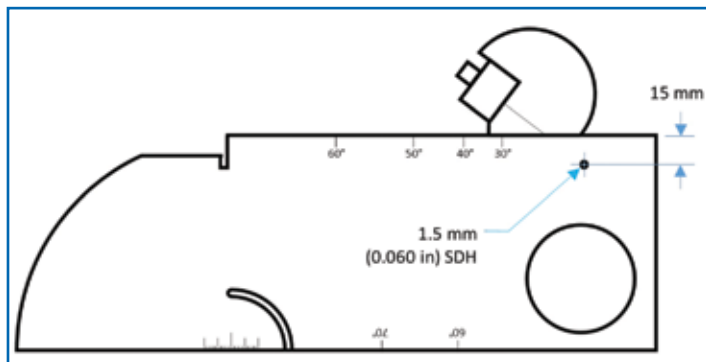


Figure 1

height (typically 50%) and that amplitude is then considered the reference amplitude. A formula is used to calculate the indication rating taking into consideration the indication amplitude, the reference amplitude, and attenuation due to beam divergence and material attenuation (Eq. 1).

$$D = A - B - C \quad (1)$$

Where:

- A = indication level
- B = reference level
- C = attenuation factor
- D = indication rating

The attenuation factor C is calculated using either formula in Eq. 2a or 2b.

$$C = \frac{SPD - 25}{12.7} \text{ mm (2a)}$$

$$C = \frac{SPD - 25}{12.7} \text{ inches (2b)}$$

The assumption in these equations is that attenuation does not begin until the sound has traveled 25mm (1 in). There are no special instructions in either the codes on how to deal with sound path distances less than 25mm, so it is assumed the same equations apply. In those cases (albeit, rare) that an indication were found at such a short sound path distance, the attenuation factor would be negative.

A quick review of the application of this equation is shown in the following example:

Example

Consider the indication shown in **Figure 2**. The reference level (B) is set at 54.2 dB and the indication level is 61.4 dB (an additional 7.2 dB above reference to bring the signal to 50% FSH). The attenuation factor C is equal to 4.5 dB, using Eq. 2a with a sound path distance of 82 mm.

Using Eq. 1 to calculate the indication rating D:

$$D = 61.4 - 54.2 - 4.5 = +2.7 \text{ dB}$$

The indication rating D would then be compared to the acceptance tables for cyclically or statically loaded structures.

Approximating attenuation in steel as a linear constant of 2dB/in makes calibration possible using a single SDH. By comparison, the use of the distance amplitude curve (DAC) or time-corrected gain (TCG) techniques

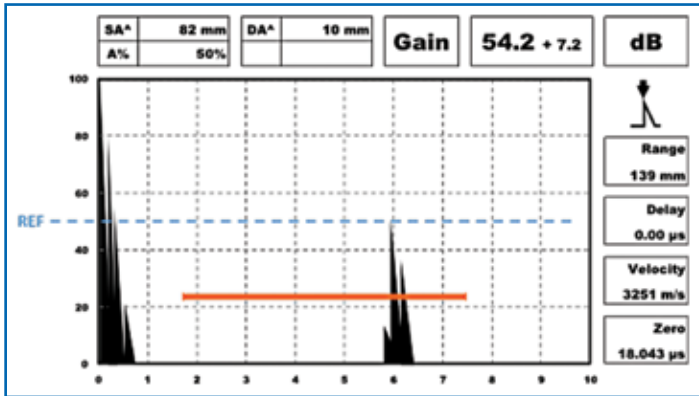


Figure 2

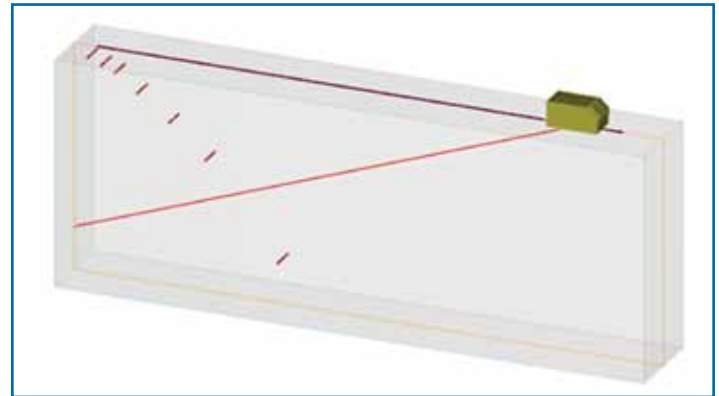


Figure 3 – Simulated block with 1.5mm diameter SDH targets

require multiple reference targets and blocks of different thicknesses. The advantages of using one block and a fixed attenuation factor come at the cost of the narrow limits placed on transducer selection, high added scanning gains, and the need to calculate the attenuation factor for every indication.

Attenuation is not linear

Attenuation is based on three primary factors: scatter, absorption and divergence. Combined losses due to **scatter** (primarily reflections off grain boundaries) and **absorption** (conversion to heat) are low in most carbon steels, on the order of 0.01dB/mm in the range of 2-4MHz that is typically used for weld inspections. The loss due to **divergence** is a result of beam spread, which is primarily a function of transducer size, angle of refraction and frequency. The compensation seen in the CSA and AWS codes is on the order of 0.08dB/mm (2dB/in). This is a factor of 8 larger than the typical material attenuation value, and is made so to account for the effect of divergence.

To illustrate the non-linearity of attenuation, CIVA modelling was used to compare the responses from AWS-style rectangular and 1/2 in diameter round probes at 45°, 60° and 70° from a 1.5mm SDH. The standard AWS probe modeled was a broadband, 2.25MHz probe with 5/8 x 5/8 in dimensions (the most common size, and also the minimum allowed by code). Also modeled was a probe with dimensions of 1 x 1 3/16 in (the maximum allowed). For comparison, 1/2 in diameter probes at 2.25MHz and 5 MHz were also modeled. The wedge sound paths modeled were the Olympus Accupath (the “big red brick”) ABWS-6 series and the Olympus short approach ABSA-5T series. Responses were obtained from 1.5mm diameter targets at 8mm, 15mm, 20mm, 38mm, 65mm, 100mm and 200mm depths.

Simulated targets were arranged in a block of steel with density 7.8g/cc. Acoustic properties included compression velocity of 5900m/s and shear velocity of 3230m/s. The attenuation values were obtained from material assessment using a through transmission technique at a nominal frequency of 5MHz. A power-attenuation law using a power of 2 calculated the attenuation at the nominal 2.25MHz used for the modelled probes.

By situating a 1.5mm diameter SDH at 15mm depth, the scan over the targets provides a direct comparison of amplitudes as they would be if using the 15mm deep 1.5mm SDH in the IIW block.

The simulated reference block was made 650mm long, 250mm deep and 100mm wide. This accommodated all but the longest scan path required by the 70° beam to reach the target at 200mm depth. See **Figure 3** for the

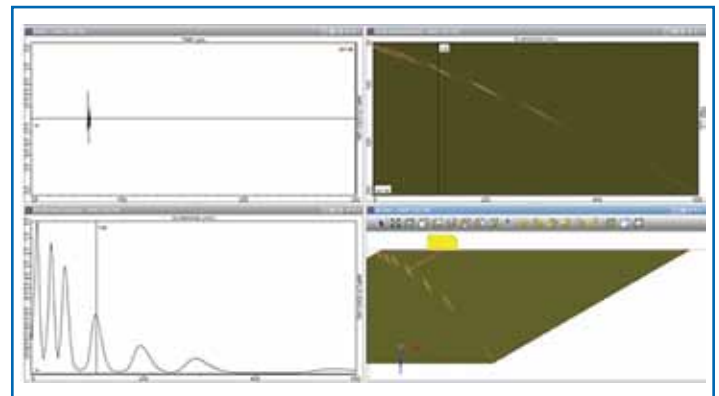


Figure 4 – CIVA data display

Top left: A-scan

Top right: B-scan

Lower left: echo-dynamic scan

Lower right: probe on block with B-scan overlay

simulated block with a 70° probe near the end of the scan.

For each probe size, a separate scan was made using a 45°, 60° and 70° beam angle. B-scans were generated and the associated A-scans could be extracted and plotted over the scan path to indicate the peak amplitude at each position (echo-dynamic plots).

An example of the plots available is illustrated in **Figure 4**.

The response from the 1.5mm SDH at 15mm depth was then used as the reference and its amplitude set to 0dB. All the other responses in the scan were then compared to the reference.

Figure 5 indicates an example where the reference amplitude is established for the second target in the scan (i.e. the 1.5mm SDH at 15mm depth).

When all the scans for the three different angles were completed and normalised to the reference target, the values were tabulated. These are graphed in **Figure 6** alongside experimental results using an Olympus C430 (5/8 x 5/8 inch, 2.25MHz) transducer on a 3/4 inch 1018 steel ASME basic calibration block. Excellent correlation is seen between the modeled and experimental data.

A few points regarding the correlation between the experimental and simulated attenuation:

- The ASME block contained reference holes of 3/32 inch (2.38mm) diameter, larger than the standard 0.060 inch (1.5mm) holes used in the simulations. However, the difference in absolute indication heights is irrelevant as only the relative dB differences are graphed. This is further explained in section on target size.

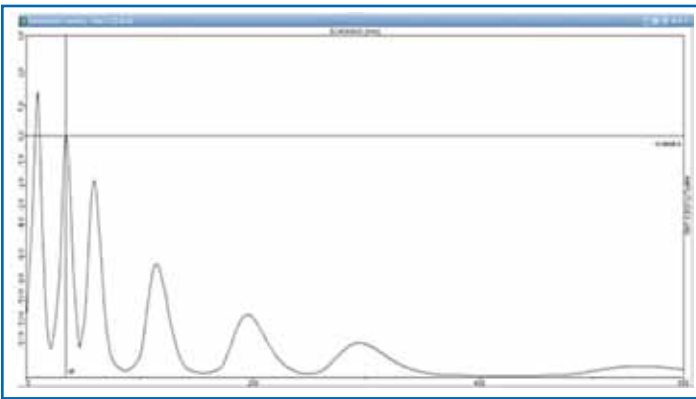


Figure 5 – Reference target set to zero dB

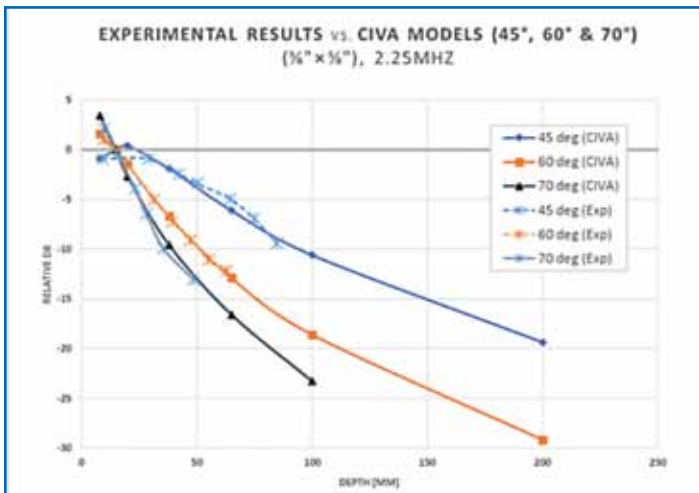


Figure 6 – CIVIA model and experimental results of attenuation

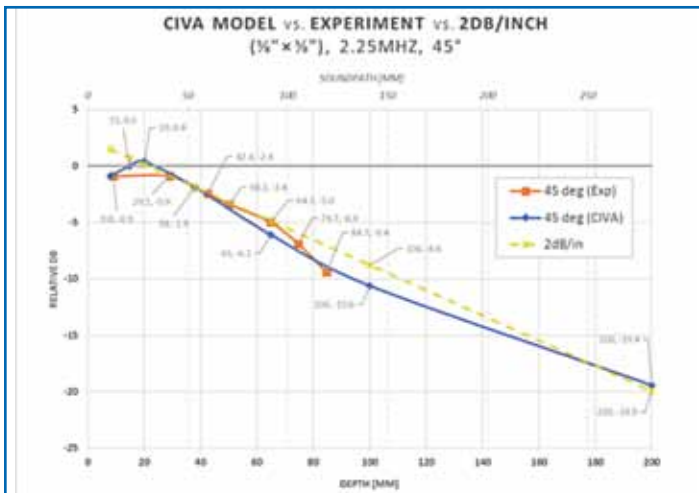


Figure 7 – 2dB/inch versus modeled attenuation of AWS probe at 45°

- In order to obtain reflections over the required sound paths, multiple reflections were required off the top and bottom surfaces of the ASME block. The losses at these surfaces has been shown to be minimal^[3]. No compensation was made in the data prior to graphing.

We can compare the relative amplitudes to the compensation made by the linear equation in the codes. Each angle incurs a different sound path, so the 2dB/inch line cannot be overlaid on a single graph of amplitude vs. depth for

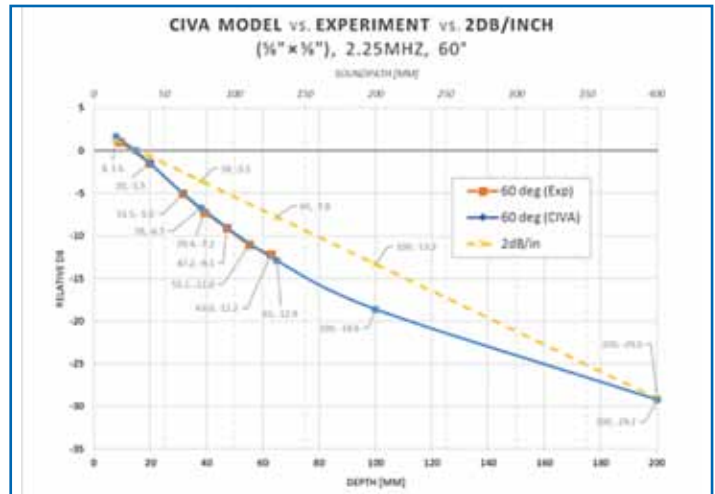


Figure 8 – 2dB/inch versus modeled attenuation of AWS probe at 60°

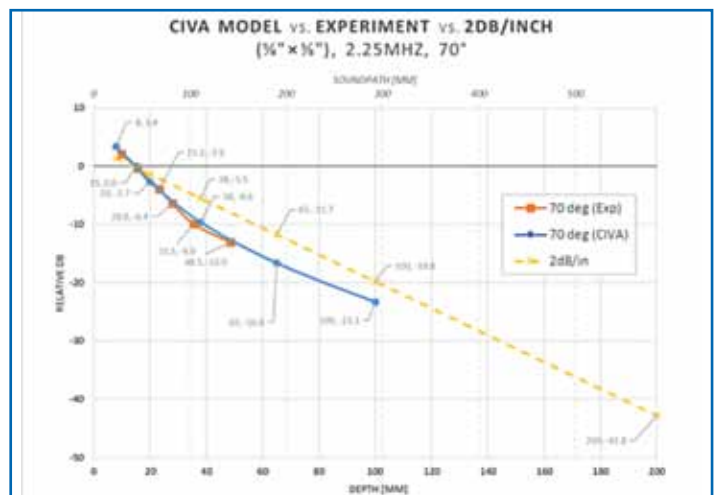


Figure 9 – 2dB/inch versus modeled attenuation of AWS probe at 70°

all three angles (as in Figure 6). A graph of each angle and the relationship to the 2dB/inch estimate is shown in Figure 7, Figure 8 and Figure 9.

In the preceding graphs, the simulations and the 2dB/in values are close only at 45° where the maximum difference is around 2dB. At 60° and 70° the differences more than double, up to nearly 6dB for sound paths of 150mm.

Effect of transducer and target parameters on attenuation

Transducer size

The size of the transducer element directly affects beam divergence. Beam half-angle is calculated by a Bessel function but can be approximated by the equation^[4]:

$$\sin \gamma = k \left(\frac{\lambda}{D} \right)$$

Where:

γ = half-angle in degrees

k = constant (derived from Bessel function)

λ = wavelength

D = diameter of the probe element

For round transducer elements, $k = 0.51$ for the -6 dB half angle. For rectangular elements the value of k changes and D is calculated separately

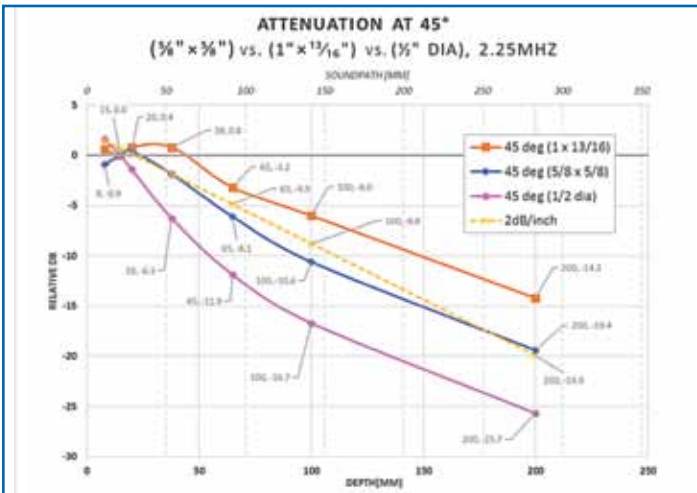


Figure 10 – Attenuation of min. and max. AWS transducer sizes at 45 degrees

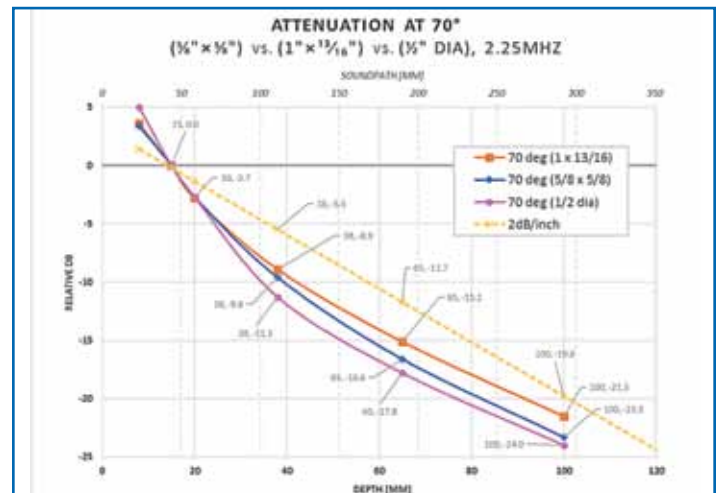


Figure 12 – Attenuation of min. and max. AWS transducer sizes at 70 degrees

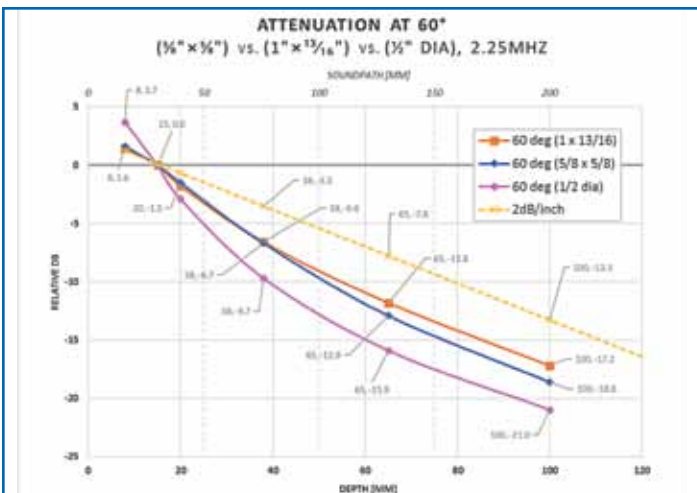


Figure 11 – Attenuation of min. and max. AWS transducer sizes at 60 degrees

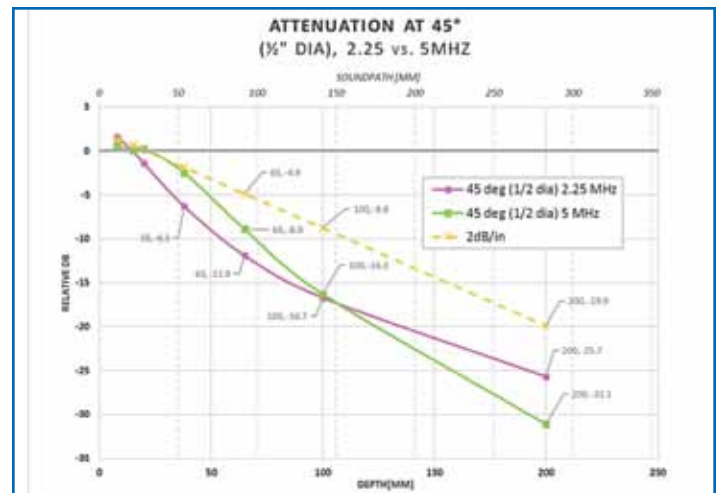


Figure 13 – Effect of frequency on attenuation (45°)

for the length and width dimension of the element.

Following from Eq. 3, we expect larger transducers to exhibit less beam spread. Less divergence would produce less attenuation. The allowable transducer sizes in the codes ranges from $\frac{5}{8} \times \frac{5}{8}$ inch to $1 \times \frac{13}{16}$ inch, making the surface area of the larger transducer more than double that of the smaller one. The difference between these minimum and maximum transducer sizes was modeled using CIVA and the results for 45°, 60° and 70° are shown in **Figure 10** to **Figure 12**. The difference between the curves is very slight, producing a difference of only 2dB at 70° and a depth of 100mm (4 in).

A more significant effect of increased probe size is observed in **Figure 10**. The larger probe has a longer near zone, and as such it appears further to the right on the X-axis. Thus, the 2dB/in model is shown to be less suited for the 1 x 13/16 inch probe than the 5/8 x 5/8 inch.

Transducer frequency

To examine the effect on attenuation of changing frequency, a second common frequency of 5MHz was modeled and compared. Since AWS transducers are not available at 5MHz, these comparisons were made using $\frac{1}{2}$ in round transducers.

Graphs of the results are shown in **Figure 13** to **Figure 15**. As expected, the 5MHz models attenuate at a considerably higher rate, which is apparent

at longer soundpaths. At 45°, the extended near zone effect is clearly seen. At 60°, the attenuation of the 5MHz and 2.25MHz are virtually identical up to a depth of 40mm.

Refracted angle

Increasing the angle has the effect of reducing the transducer height, which in turn increases beam spread and thus attenuation. It is therefore expected that higher angles will exhibit more attenuation. This is evident in both the experimental results and CIVA simulation results (refer to **Figure 6**).

Note: Increasing angle of refraction reduces effective transducer dimension (Dim)_{eff}, thus increasing beam spread

Target size

CSA and AWS use only the 0.060 inch (1.5 mm) hole, while codes such as ASME Sec. V Article 4 make use of a variety of hole diameters ranging from 3/32 inch (2.5 mm) to 3/16 inch (5 mm) for welds up to 4 inches (100 mm) thick.

To demonstrate the effect of side-drilled hole diameter, a simulated 16x16mm probe was scanned over a series of 3mm diameter SDHs in the same positions as was used for the 1.5mm diameter SDHs. Results seen in **Figure 17** for 70° (where the maximum difference was seen), indicate that

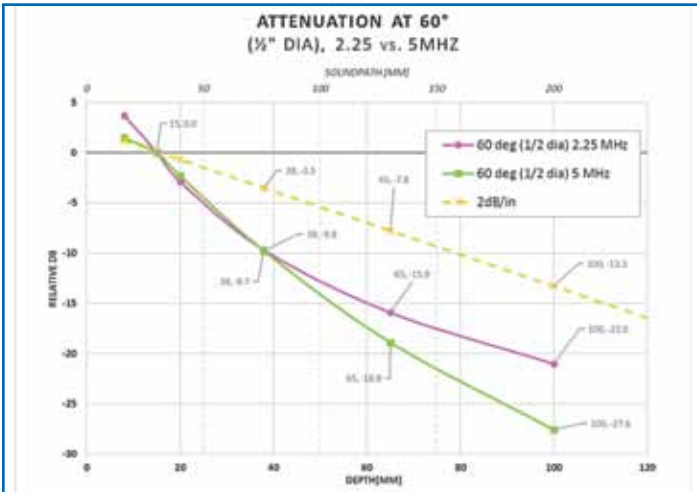


Figure 14 – Effect of frequency on attenuation (60°)

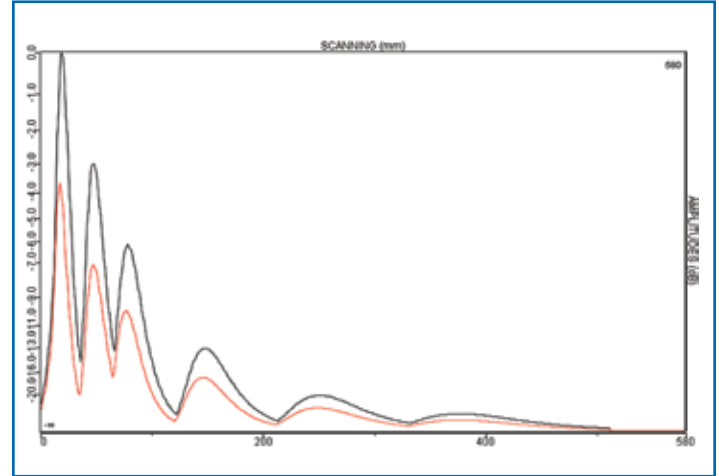


Figure 17 – Relative amplitude responses of a typical AWS transducer on 1.5mm (red) and 3mm (black) diameter SDHs

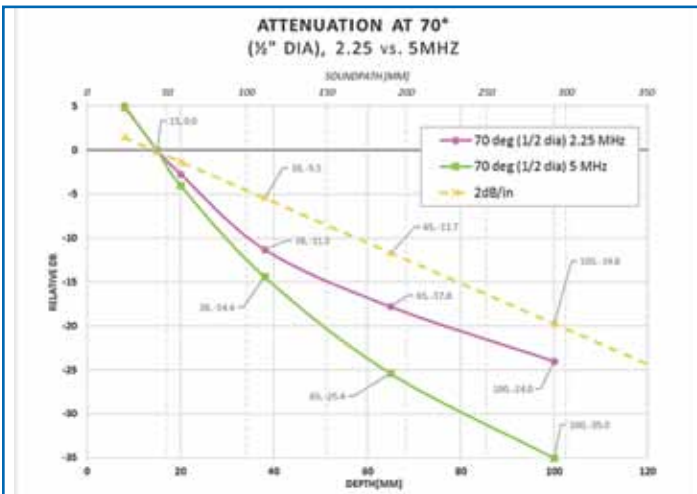


Figure 15 – Effect of frequency on attenuation (70°)

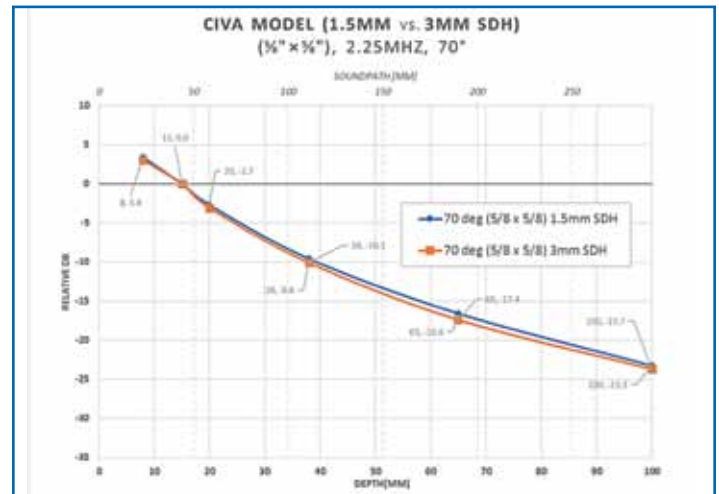


Figure 18 – Attenuation of 1.5mm and 3mm SDH at 70°

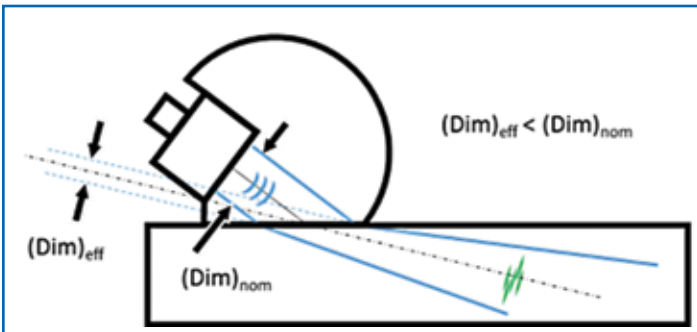


Figure 16 – Effect of angle of incidence on beam spread

Conclusions

The 2dB/in model has been in effect for nearly 50 years, beginning in AWS D1.0 (1969) Appendix C^[6]. A close look at the details of attenuation reveals that the factor is simply an empirical fit that approximates the effect for a typical probe. The model has served industry well for many years, but technology and understanding of ultrasonic physics has long since surpassed the need to restrict users to a “one size fits all” model. This is especially true, since the 2dB/in model does not model particularly well the transducer size range and angles for which it is intended. The time has come to put North American structural ultrasonic inspection techniques at par with practices used worldwide and revise the techniques and acceptance levels for use of a DAC/TCG for attenuation.

By understanding the effects that angle, size and frequency have on attenuation, the impression of the 2dB/in factor on the ultrasonic acceptance levels can be quantified. This permits the development of alternate techniques, adapting the acceptance levels for use of a wide variety of transducers and will produce more repeatable results. As well, alternative hole sizes to the 1.5mm diameter SDH presently used by CSA/AWS are feasible in that they provide an easily calculated difference based on diameter that is consistent over the full range of sound paths for the same probe.

the rate of attenuation is essentially identical. Note that in this figure, the response from the 3mm hole is about 4dB greater than the 1.5mm hole, but the attenuation rate remains unaffected. This data is plotted in **Figure 18** where only a 0.8 dB difference in attenuation rate was found at a soundpath distance of 65mm.

When the comparisons are made with the amplitudes normalised to the 3mm diameter holes the effect is as predicted by Ermolov^[5] in that the amplitude difference is a constant value regardless of the soundpath.

Acknowledgements

I would like to thank Ed Ginzel for his contributions. Much of this paper was inspired (and directly lifted from) ongoing correspondence between us related to ultrasonic testing. Ed also provided all the CIVA modelling data.

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