Errors resulting from curved phased-array wedges

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Abstract
Ultrasonic operators have long struggled with the problems associated with setting sensitivity when inspecting pipe girth welds on small diameter pipe. Issues have been compounded with the introduction of S-scans used by phased-array techniques. This article describes how the solution by some technicians to calibrate using a flat wedge and then change the wedge to a contoured wedge for the actual scanning can lead to errors. Recommendation is made for a codified approach.

Keywords: pipe girth welds, phased-array, S-scans

1. Introduction

Butt weld inspection is perhaps one of the most common applications of the UT method. Pipe girth welds are nothing more than butt welds joining cylinders. But as the diameter of the cylinder gets smaller the simple weld inspection takes on added dimensions of complexity. The first item seen to deviate is the contact area between the pipe and probe. The European norm EN 1714 instructs that for gaps greater than 0.5mm the probe wedge is to be contoured. It is at this point the problems begin for the ultrasonic operator. UT codes around the world have a common list of required assessments and also stipulate the calibration blocks that are to be used for these assessments. But all these measurements seem to be based on the assumption that the probe will be used on a flat surface. Verification of beam angle, exit point, beam spread assessments and even temporal resolution are described in the codes with the associated calibration blocks including, the IIW block, the V2 block and the IOW block. All have flat surfaces. But upon inspecting a pipe girth weld, none of the required measurements can be made when the probes used are fitted with contoured wedges.

When the weld inspection is to be made with a phased-array probe some of the “traditional” assessments cannot be made. E.g. there is no exit point marked on the phased-array wedge against which to compare a measurement. Checking the refracted angle against the “indicated angle” marked on the wedge is also without meaning since most any angle can be generated.

To a large degree, these differences can be overlooked as a result of the two dimensional fan-shaped display provided on the monitor for an S-scan. The coordinates (depth and offset from a probe reference) can be displayed on the monitor and these values compared to the targets’ known depth and physical offset relative to the probe. This comparison can be done on any block with a side drilled hole (e.g. the IOW block). The wedge delay and velocity settings for the focal law group provide an image of the relative position and the S-scan display results are compared to the target as in Figure 1 where the S-scan display illustrates a 1.5mm diameter SDH at 19mm depth located by the software cursors as being a 19mm depth using the 55° focal law.
If the exact velocity and dimensions are known for the wedge it is conceivable that a close approximation of the wedge delay time could be calculated. Although the “published values” may get the computations close to the correct values, the published values should only be considered approximate. Some software utilities use the fixed depth of a SDH to calculate the delays that compensate for the time in the wedge. Using a SDH and the type of display seen in Figure 1 is a convenient check on the accuracy of the delays applied to the screen display that compensate for the increased time that the pulse is in the wedge material as the refracted angle is increased.

Since there are no standard calibration blocks with curved surfaces, some operators have decided it would be a good idea to simply set the wedge-delays and TCG (sensitivity compensation) using a flat wedge and then remove the flat wedge and replace it with the wedge curved to match the test surface of the pipe that is to be inspected. The process is rationalised by using a wedge having the same material and wedge path as the centre of the beam for the flat wedge.

In spite of the common sound path in the wedge, differences can result for both the delays and the sensitivities established using flat wedges on flat surfaced calibration blocks.
2. Calibrating the S-scan

The rationale for using the curved wedge after calibrating with a flat wedge seems to be based on the Fermat equations used to establish the focal laws. These are based on calculating the time in the wedge material and the time in the test material. This requires operator input of the wedge velocity and the test piece velocity for the mode being used. Some geometric information is required as well. In particular there is a reference distance and angle on the wedge (e.g. the height of the first element over the test piece and the machined incident angle). Wedge path along the centre ray is deemed the only criteria necessary to rationalise this practice. The equal wedge-paths are indicated in Figure 2.

![Figure 2](image)

*Figure 2  Maintaining wedge-path for curved wedges.*

Essentially the curved wedge is made by using a thicker section of wedge material and milling the curvature back to where the apex has the same distance to the array as if the probe had been flat.

The assumption that only the centre ray is important is perhaps a reasonable first approximation. But for a linear phased-array probe, the wavefront is a result of constructive interference. Subtle differences in the wedge material, the fact that the probe has been re-coupled to a new wedge and the lateral components of the wavelets as they interact with the wedge/metal interface can all be factors that alter the assumed simple equivalence for the Fermat solutions to the focal laws.

Compare the ray tracing of a beam of rays leaving the flat probe on a flat surfaced plate. All have the same time of arrival at the plate surface and no refraction occurs laterally. The wavefront therefore impinges on the SDH at the same time and at nearly a perpendicular angle all across the SDH length.

However, when the shaped wedge is placed on a curved surface the beam of rays is seen to provide a refraction laterally at the interface (i.e. following Snell’s Law). This situation results in a further divergence at the SDH due to the lateral portions reflecting away from the centre. These two conditions are illustrated in Figure 3.
The centre ray is the shortest time in the wedge and ideally follows the same path distance in both the flat and curved wedges. Therefore the arrival time back to the probe is “ideally” the same. This would imply that the wedge-off set calculations provide target depths at identical locations when a curved wedge replaced a flat wedge.

To test this assumption a probe was calibrated for an S-scan (45° to 70°) using a flat wedge designed for the 5MHz 16 element probe. All adjustments were made including wedge delay, velocity check, and a four-point TCG on the IOW block 1.5mm diameter SDHs.

A pair of custom calibration blocks was made available for comparison. Both these blocks had a SDH 1.6mm diameter at the same depth from the test surface. The difference being that one block had a flat surface and the other was curved with a diameter of 2.375” (60.3mm). The 2 custom blocks are seen in Figure 4 with the 1.6mm SDH highlighted.

After the probe with the flat wedge had been calibrated using the IOW block targets to construct the TCG, an encoded scan was made over the SDH in the flat surfaced block with the 1.6mm diameter SDH. As predicted the response was nearly identical to the TCG for a hole at that depth. The difference in SDH diameter between the IOW block and the custom
calibration block was only 0.1mm. No significant difference would be detected in amplitude response.

Scanning of the SDH in the custom blocks was done using an encoder and scan motion perpendicular to the SDH long axis such that each angle in the focal law set would pass a point where a maximum returned echo would occur. Figure 5 illustrates the Composite End View plot of the scan. This indicates the maximum amplitude of the SDH 19mm under the test surface as it passes through each of the focal laws from 45-70°.

Apparent from this image is the uniformity of the amplitude of the target as seen by each angle. There is a maximum of 90.2% screen height and minimum of 83.5% screen height responses over the full scan through all the angles. This small variation of less than 1dB can be attributed to a very well constructed ACG (angle corrected gain) compensation and TCG (time corrected gain).

Also apparent is the uniformity of the peak arrival time. This indicates the depth of the target as seen by each angle. In every focal law the peak amplitude is indicated as being 19mm depth.

![Composite End View of scan of SDH on flat block](image)

*Figure 5*  
Composite End View of scan of SDH on flat block

Data displayed in Figure 5 was at reference level as determined from the TCG as set using the 1.5mm diameter SDHs.

Having demonstrated the suitability of the wedge delays and sensitivity on the flat custom block, the operator then removed the flat wedge and coupled the curved wedge to the probe. This wedge had the identical centre wedge path distance as the flat but was contoured to match the curvature of the block with the SDH seen in Figure 4 (2” NPS has a 60.3mm diameter). No adjustments were made to the wedge delays, velocity settings or the gain settings.

Scan results for the curved block were presented in the same composite end view (seen in Figure 6).
From the image in Figure 6 it is apparent that the amplitude response is significantly lower at all angles. As well, the amplitude response seems to drop off as the SDH crosses through the upper angles. Further differences between the image in Figure 5 and 6 relate to the arrival times of the peak signal from each angle. The 45° beam sees the peak signal at a depth of 20mm (19.9mm) and a gradual trend of increasing depth is seen to 70° where the peak occurs at 23mm.

Figure 7 is the same presentation as was provided in Figure 6 but with an additional 7.2dB of software gain added to bring the 45° response up to 88% screen height.

The contoured wedge was removed and re-coupled and the test was run again. The time (depth) parameter saw improvements in that the assessed depth of the SDH with the curved
wedge was within +/-1mm of the true depth along the length of the scan. Amplitude response was still well off the reference set by the flat wedge (requiring 5.4dB to get the 45° focal law to get an 88% response from the SDH).

3. Modelling

Civa simulation software was used to investigate the effects of curvature on the amplitude drops associated with the S-scan.

As noted, scans on the custom blocks used both ACG and TCG corrections. ACG is accomplished first by equalising the response of the 100mm radius of the IIW block for all the angles in the focal law group (45°-70°). ACG compensate for echo-transmittance differences of the angles used. After the ACG is made the instrument is then configured with a TCG to compensate for the effects of increasing distance to the target. Increasing distance occurs as the operator detects SDHs at greater depths. But it also occurs for the same SDH as the angles increase. ACG is not a function built into the simulation software so an assessment of the degree of change was made by first modelling the flat surface scan.

The Civa model used a 1.6mm diameter SDH in a plate at 19mm depth and the S-scan used 11 focal laws from 45° to 70° with a scanning direction that had the 70° focal law encounter the SDH first. This scan was repeated for the SDH in the block with a 60.3mm diameter (equivalent to a pipe 2” NPS). The setups are seen in Figure 8.

Figure 8  Plate and curved surface models for SDH at 19mm depth

Plotting the maximum amplitude from the SDH for each angle obtains a so-called Echo-dynamic C-scan. This is illustrated in Figure 9 for the SDH in the plate. The probe position is plotted along the horizontal axis and at each scan increment the maximum amplitude from any of the angle beams is plotted on the vertical axis. This curve provides an indication of the degree of compensation required for the combined effects of ACG and TCG.
A similar echo-dynamic curve is made for the scan on the 60.3mm diameter curved surface and the dB drops are noted relative to the peak (at 45°). Plotting the dB drop of the flat plate scan and the curved surface scan provides an indication of the combined effect of echo-transmittance and distance attenuation for the two blocks. This is compared in Figure 10.

Error bars in Figure 10 placed on the flat surface values indicate 1dB variation. Most points from the curved surface are within that 1dB range.

However, when the absolute values are compared the effects of lateral refraction and scatter are added to all points. In addition to the flat plate and 60.3mm diameter surfaces, the model was extended to examine what would happen if the surface diameter was increased. Figure 11 compares the curves for four conditions:

- Flat
- 20” NPS (508mm diameter)
- 6” NPS (168mm diameter)
- 2” NPS (60.3mm diameter)
For the angles from about $45^\circ$-$50^\circ$ where little or no extra gain is added in the ACG and TCG process, the graph in Figure 11 shows good correlation between the amplitudes observed for the responses from the flat and 60.3mm diameter surfaces in Figure 5 and 6. There it was noted that upon re-coupling the curved wedge to the probe 5.4dB was required to bring the $45^\circ$ signal on the curved block up to that on the flat. The “ideal” modelled conditions indicate a 3.5dB drop might be expected.

**4. Conclusions**

Use of contoured wedges introduces uncertainties in the inspection process when they are not possible to calibrate using standard techniques comparing responses to reflectors of known depth.

Uniformity of acoustic velocity and actual dimensions of the curved wedges compared to the flat wedges used for setup cannot be assured. Small variations associated with coupling the wedge to the probe can also be introduced. Depth variations seen in this example are within a relatively small range and may be adequate for many applications.

Most significant is the effect on amplitude response. Lateral refraction significantly alters the beam shape in cylinders (pipe) compared to plate. This implies that sensitivity setups made on plate are not maintained when switching to curved wedges for curved surfaces.

Although there appears to be preservation of the relative responses of a target with reduction in surface radius, the absolute differences will still require some method of comparison once the curved wedge replaces the flat wedge that was used for the ACG and TCG calibrations.

Models and experiments for this demonstration are very limited. More work should be carried out to assess the effects on different probes and targets. Also, the process needs to be codified in UT standards to overcome the present shortcomings in setting sensitivities on curved surfaces for phased-array probes.