Comparing Responses from Slot, Side-Drilled Hole and Curved Hole Targets in Ultrasonic Reference Blocks

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Abstract
The cylindrical shape of side-drilled holes (SDHs) make them ideal as calibration reflectors. However, when used within curved reference standards such as those for piping, they exhibit only one tangent point and thus require accurate probe positioning during calibration. Use of curved holes, such as those that might be created using electro-discharge machining methods, would produce the same target shape at all positions along their length and would eliminate the need to locate a precise tangent point, thus simplifying calibration. However, machining curved holes in pipe can present some difficulties and considerable added expense. The authors examine variations on the SDH using curved slots (simulating a curved hole parallel to the inside and outside surfaces) and a straight slot machined from the end of the pipe. Civa simulations and laboratory tests indicate that the straight ball-end slot and SDH behave as essentially identical reference reflectors. The curved slot, simulating a curved hole, produces varying degrees of convergence and divergence which does not produce equivalence to a traditional SDH. The difference is mainly due to beam aperture in the lateral direction, with increasing beam size (or effective probe width), producing greater differences.

Keywords: Side-drilled hole, calibration targets, ultrasonic, pipe, ASME, phased array

1. Introduction

Typical reference targets for weld inspections by ultrasonic test methods are flat bottom holes, surface notches or side-drilled holes. Side drilled holes (SDHs) are usually preferred [1, 2, 3], especially for phased-array techniques because they present the same cross-section regardless of the angle of incidence from the beam.

A concern that some users have relates to the fabrication of the SDH when placed in a pipe. The depth of the target is correct only for the tangential location. Thus, the operator must carefully place the probe directly over the tangent point to establish reference sensitivity.

It has been suggested that using the same diameter hole but fabricating it as a curved hole parallel to the pipe inside and outside surfaces would provide easier calibration because the operator would not have to worry about locating the tangent point. In spite of the perceived convenience to the ultrasonic operator that a curved hole might have, there appears to have been no consideration to the effect that this geometry might have on the sensitivity of a scan setup. Perhaps more pertinent than convenience to the operator, the cost of such a target would be much greater than the straight

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side-drilled hole. Such a target would require careful preparation using electro-discharge machining (EDM). A viable option to the curved EDM hole is considered in this paper. A curved slot would have all the same characteristics as the curved hole but would be much easier to machine using either an EDM process or a ball-end mill cutter.

This paper describes how Civa modelling was used to compare ultrasonic responses on the traditional SDH in pipe to the responses from a cylindrical slot and a curved slot. Having demonstrated the results using Civa modelling, experimental results were carried out to validate the modelling. Advantages and disadvantages of the options are then discussed.

2. Modeling Hole Responses Using Civa

Civa modelling has been used to illustrate the sensitivity differences between SDHs, cylindrical slots and curved holes. These target forms were generated using the Civa CAD utility to simulate aspects of the lab model described later in this paper.

Modelling parameters used included:

- Probe: 6 mm diameter, 5 MHz on 60° and 70° refracting wedges
- Material: Steel $V_{long} = 5900 \text{ m/s} (0.2323 \text{ in/μs})$, $V_{shear} = 3230 \text{ m/s} (0.1272 \text{ in/μs})$
- Target: 2 mm (0.079 in.) diameter placed at ½T thickness
- Targets consisted of the standard Civa canonical form for SDHs, an extruded multi-faceted flaw for the cylindrical slot and rotational extrusion for the curved slot and hole

Figure 1 illustrates a rotationally extruded hole made 25 mm from the end of the pipe. This was used to simulate the target that would occur by using a curved wire electrode to EDM erode a hole parallel to the pipe surfaces. The standard Civa side drilled hole (SDH) was placed sufficiently far back from the curved hole to allow the scan to interact with the targets separately.

Figure 2 illustrates a rotationally extruded curved slot. This has all the features of the curved hole but can be made using a ball-end mill cutter or a suitably formed electrode for EDM. The standard Civa SDH was again placed back from the extruded slot.

Figure 3 illustrates the cylindrical slot. This was simulated in Civa using a multifaceted 2D extruded flaw. In the lab, this target can be made using a ball-end mill cutter or a suitably formed electrode for EDM. It has essentially the same geometry with respect to the beam as the SDH; however, since the curvature is not continuous around the target, the creeping wave cannot return to the probe but remains linked to the Rayleigh wave and moves to the end of the pipe, undetected.
The echo dynamics for 60° and 70° beams were used on the results of simulated scans to analyse the relative amplitudes of the targets. By having arranged the scans to provide both the typical code compliant SDH target and the target variation in the same scan, a direct comparison of amplitudes could be made. Figure 4 shows how the echo-dynamic curves can provide the relative amplitudes with respect to the traditional SDH.
Figure 4: 60° 5MHz on 150mm OD 12mm wall thickness – cylindrical slot versus SDH

A summary of the relative amplitudes is provided in Table 1 for several simulations.

Table 1: Specimen models

<table>
<thead>
<tr>
<th>Simulation #</th>
<th>Angle (deg)</th>
<th>Pipe dia. &amp; thickness (mm)</th>
<th>Targets*</th>
<th>Amplitude (dB)**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1st half skip</td>
</tr>
<tr>
<td>1</td>
<td>60</td>
<td>150 x 12</td>
<td>SDH/CS</td>
<td>0/+1.6</td>
</tr>
<tr>
<td>2</td>
<td>60</td>
<td>150 x 6</td>
<td>SDH/CS</td>
<td>0/+1.9</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>200 x 9</td>
<td>SDH/CH</td>
<td>0/+1.6</td>
</tr>
<tr>
<td>4</td>
<td>60</td>
<td>100 x 6</td>
<td>SDH/CH</td>
<td>0/+1.3</td>
</tr>
<tr>
<td>5</td>
<td>60</td>
<td>100 x 9</td>
<td>SDH/CS</td>
<td>0/2.0</td>
</tr>
<tr>
<td>6</td>
<td>70</td>
<td>100 x 6</td>
<td>SDH/CH</td>
<td>0/+1.7</td>
</tr>
<tr>
<td>7</td>
<td>70</td>
<td>150 x 6</td>
<td>SDH/CS</td>
<td>0/+1.7</td>
</tr>
<tr>
<td>8</td>
<td>70</td>
<td>150 x 9</td>
<td>SDH/CS</td>
<td>0/+1.7</td>
</tr>
<tr>
<td>9</td>
<td>70</td>
<td>150 x 12</td>
<td>SDH/CS</td>
<td>0/+1.6</td>
</tr>
</tbody>
</table>

*SDH=side drilled hole, CH=Curved hole (or slot), CS=cylindrical slot

**Amplitude uses SDH as reference 0 dB and positive values indicate signals greater than reference
Data from Table 1 is used to generate the plot in Figure 5. The plot illustrates the relatively small variation of responses for the alternative targets (CH/CS) relative to the standard SDH.

![Comparing Amplitude Responses Relative to SDHs](image)

**Figure 5: Comparing amplitude responses to SDHs (normalised to the direct path to a SDH)**

Based on the limited observations made using Civa simulations, the sensitivity variation between SDHs and curved holes is generally small. Findings suggest that sensitivities established using SDHs and curved holes or cylindrical slots could, for the purposes of calibration reference, be considered equivalent for small, round mono-element probes. Costs relating to the fabrication have not been investigated however, compared to the cost of EDM for the curved hole made using a wire, the ball-end-mill shapes are expected to be less.

During the research, simultaneous Civa modeling and experimental testing revealed increasing differences when applying phased array testing which used wider, rectangular aperture probes. Using larger rectangular apertures on small thickness and small diameter pipe risks that the target and even the points of reflection on the pipe inner and outer surfaces will occur in the near field. For these larger apertures, near field lobes were found to cause greater variation between the different target shapes.

### 3. Practical Experiment

A test specimen was designed by Holloway NDT & Engineering Inc. and manufactured by PH Tool Reference Standards to compare SDH and curved holes. The piece featured three targets for comparison: a standard side drilled hole, a straight ball-end slot meant to simulate a SDH, and a
curved ball-end slot to simulate a curved hole. Straight targets are easily made using standard machining methods, however true curved targets like a curved hole would require a complex and expensive electro-discharge machining (EDM) operation using a curved electrode. As such, the curved slot (and, for convenience, the straight slot) were formed using EDM.

The outside diameter (OD) of the specimen was 114.3 mm (4.5 inches) and the wall thickness was 8.6 mm (0.339 inches) made to represent a 4-inch Sch. XS/80 pipe section (Figure 6). The diameter of each reference target was 1.6 mm (1/16 inch).

Figure 6: CAD model and photograph of practical test specimen

Figure 7 details the reference targets. Section A-A represents a simulation of a curved hole using a rounded EDM electrode. Section B-B is a simulation of a side-drilled hole, again using the same rounded EDM electrode. Finally, a simple side-drilled hole is shown in Section C-C.

To fully examine the target responses, phased array ultrasonic testing (PAUT) was used to generate a range of angles from 45° to 70° with a 1° increment.

Equipment used:

- Sonatest Veo+ 32:128 phased array flaw detector
- Olympus 5L16-A10 transducer (5 MHz, 16-elements, 0.6 mm pitch)
- Olympus SA10-N55S-4.5AOD wedge (AOD contour of 4.5 in. to match test piece)
- Water irrigation system
To simulate a typical PAUT focal law, the beam was focused at a fixed (true) depth of 1.5 times the part thickness, or at 12.9 mm (0.508 in.). Thus, the beam was focused essentially at the center of the 1.5 T hole.

A time corrected gain (TCG) calibration was performed first on the side-drilled hole target with calibration points at the 0.5T, 1.5T and 2.5T positions. The straight slot and curved slot targets were then scanned and the responses relative to the side-drilled hole compared (Figure 8).

Precise beam positioning on the tangent points of the SDH and straight slot was essential to obtaining stable and repeatable responses. This was, as discussed previously, irrelevant for the curved slot target. Each target was scanned multiple times and a table of results was compiled with the average amplitude responses tabulated in 5° increments (see Table 2).
The straight slot target did not display any appreciable differences from the standard side-drilled hole. This was the expected result, as the shape of the surfaces facing the beam at the point of impingement are identical. Figure 9 illustrates the results where it can be seen there is less than 2 dB difference at all angles and target depths.

Table 2: Comparison of amplitudes for straight and curved slot targets relative to SDH

<table>
<thead>
<tr>
<th></th>
<th>Straight Slot (rel. to SDH, dB)</th>
<th>Curved Slot (rel. to SDH, dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5T</td>
<td>0.6 - 0.7 - 0.8 - 0.6 - 1.5</td>
<td>0.3 - 0.7 - 0.2 - 0.8 - 0.0</td>
</tr>
<tr>
<td>1.5T</td>
<td>0.0 - 0.5 + 0.6 + 0.0 - 0.4 - 0.4</td>
<td>+ 2.2 + 2.1 + 3.2 + 3.4 + 3.6 + 4.1</td>
</tr>
<tr>
<td>2.5T</td>
<td>+ 0.2 - 0.7 - 1.4 - 1.0 - 0.2 - 0.7</td>
<td>- 8.7 - 8.5 - 7.2 - 6.7 - 4.2 - 4.1</td>
</tr>
</tbody>
</table>
The curved slot target, meant to simulate a curved hole, did reveal a larger difference compared to the side-drilled hole. These differences varied depending on the target depth (Figure 10).

At the 0.5 T hole, the beam is hitting the curved slot target which is convex, producing a *diverging* effect. The response at this position is affected only a minor amount, with deviations from the
SDH target of up to -3 dB. In practical terms, such a small difference may be considered negligible and it could be said that the difference, although more pronounced than that of the straight slot, could still be considered equivalent in practice to a SDH.

Upon reflecting from the inside surface of the pipe, the beam then impinges upon the curved slot target at 1.5 T which is then seen as a concave profile. This would be expected to produce a converging effect upon reflection and effectively amplify the target response. This is observed as the rise in the middle of Figure 10. The curved target produces a response of between +2 and +4 dB greater than the SDH.

At the 2.5 T hole after the 2nd skip (off the OD), the shape of the target is then again convex as it was at the 0.5 T position. This produces divergence again, and the result is even more pronounced as the difference ranges from -4 to -9 dB.

4. Conclusions

The Civa modelling and the experimental tests were not exhaustive, and many factors were discovered during the research that contributed to the results. The effect of probe size (and thus near zone length) and shape (circular vs. rectangular) were the main sources of differences observed between target responses.

Probes with rectangular aspect ratios, such as those used in phased array, may exhibit side-lobes in the near zone Figure 11). It is not until well into the far field (Fraunhofer zone) that the beam develops into a relatively uniform profile across the width, with the maxima at the beam center.

Figure 11: Beam side lobes produced by a rectangular aperture probe in the near field
By moving the probe laterally and passing the beam across a through wall hole (TWH) in a plate, side lobes can easily be observed (Figure 12). This evaluation was performed using a time encoded scan for visualization of lobe effect only; no measurement of beam width was intended.

The side lobes will decrease with increasing sound path and the prominence will vary depending on the aperture aspect ratio (e.g. differing element usage in PAUT) and frequency. These side lobes produce unstable amplitude values as the transducer, even unintentionally, is skewed slightly. Even a barely imperceptible amount of skew while calibrating may produce amplitude variations greater than 2 dB.

The side-drilled hole and straight slot are equivalent targets. Regarding the curved slot (or curved hole), limiting the range of sound path used, and restricting probe shape and aspect ratio may reduce the effects of divergence/convergence off the curved target surface to a point where the curved slot (or curved hole) would be considered effectively equivalent also. However, without a more comprehensive evaluation of the effect of many parameters (transducer size, shape, aspect ratio, frequency, focal distance, part curvature), it is not possible to state for all cases in which the difference would be small enough to be considered equivalent.

Besides the theoretical study, there is the question of code acceptance of curved holes as reference targets. Presently in ASME Sec. V Article 4, the recognized standard targets for sensitivity calibration are only the notch and the straight side-drilled hole. Curved holes are not permitted as a standard option, but there is allowance for alternative reflectors as per T-434.1.1 which states in part: “An alternative reflector(s) may be used provided that the alternative reflector(s) produces a sensitivity equal to or greater than the specified reflector(s)”. It has been shown in this paper that curved hole reflectors may be equivalent (as an example, to within ±2 dB) to side-drilled hole targets only when the probe and beam parameters are controlled well enough to limit the differing effects the curved target produces. The curved hole not only produces convergence and divergence...
effects that flat targets do not, it also produces different travel times for parts of the beam off the center axis as compared to flat targets, which will produce different resultant excitation of the crystal(s).

It is concluded that curved holes should generally not be considered equivalent to side-drilled holes except in very limited applications.

5. Acknowledgements

We would like to thank the staff at Extende for their ongoing support with Civa simulations and El Mahjoub Rasselkorde for assistance with the multi-faceted flaw extrusion. We would also like to thank PH Tool for supplying the sample with machined targets used to validate this project.

References

1. American Society of Mechanical Engineers, Boiler and Pressure Vessel Code, Section V, Art. 4, Published in New York, New York, USA, 2019

2. ISO 16811, Non-destructive testing — Ultrasonic testing — Sensitivity and range setting, Published by BSI Standards Limited 2014

3. ISO 13588 - Non-destructive testing of welds — Ultrasonic testing — Use of automated phased array technology, European Committee for Standardization, Brussels, 2012