# Comparison of Side Drilled Holes and Surface Notch Response for Phased Array Sectorial Beams Calibration Process

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## Abstract

In this work, Phased array ultrasonic testing (PAUT) is calibrated for sound velocity, wedge delay, sensitivity and time corrected gain using side drilled holes and notches as reflectors. The responses of the reflectors for various angles (40 – 70$^{o}$) are studied and standardised. The significant use of these reflectors and the cause of non-uniformity in notches, are analysed by comparing the reflection property of side drilled holes and surface notches for useful range of sectorial beam sets. Results are validated with the simulation studies.

***Keywords***: *Phased array UT; Side drilled hole vs flat bottom hole; PAUT calibration for pipe welds*

**Introduction:**

Phased array ultrasonic testing (PAUT) is a significantly growing advanced ultrasonic testing technique and is replacing other conventional techniques in several applications [1] The phased array probe could generate multiple angles sequentially to identify the volumetric defects present in the components. The use of multiple beam angles would increase the probability of finding the mis-oriented defects [2]. Equipment and Probe selection play a vital role in inspection. The effects of probe and equipment parameters on inspection results are well known to PAUT users [3]. Similar to conventional ultrasonic testing, the probability of the reflected sound reaching back the probe depends on the defect orientation and the sound beam orientation. The beam angle range is selected based on weld bevel details and the probable defect orientation that could occur in the welding process. The beam incident angle could be selected as optimum angle +/- 10 degree for most of the testing [4]. The inspection coverage and effectiveness of focal law depend on the scan plan [5] prepared for the inspection zone. In addition to this, calibration plays a vital role similar to any other NDT techniques.

Standardisation/Calibration of equipment to suite the job requirement is comparatively simple in conventional ultrasonic testing. Distance amplitude correction curve (DAC) is widely used for conventional UT standardisation. While performing DAC calibration in conventional UT, calibration is to be performed for only one beam angle. Whereas, in phased array sectorial scanning, multiple angles will be generated and all the angles have to be calibrated within a same calibration set up. Performing the calibration, manually, in phased array, is cumbersome as it involves multiple angles. Therefore, the calibration process is supported by the equipment to bring to the range calibration (velocity calibration and Wedge delay calibration) and gain calibration (Sensitivity and TCG) [6]. **The Velocity calibration** is used to determine the actual sound velocity in the material, **Wedge delay calibration** is for compensation of variation in the travel distance within the wedge for different angles [6]. **Sensitivity calibration** is for compensation of energy loss within the wedge for all angles and **Time corrected gain calibration- TCG** is for compensation of energy loss for different angles and various depth, due to attenuation in material).

During the phased array calibration process, a reflector is detected by all the beams sequentially and the system will provide corrections to bring the indication to a uniform standard level [6]. This is performed for all waveforms (i.e. focal laws/ angles) present in the beam sets/group. The detection and the severity of defects depend on the type and size of the reference reflector used during the calibration. Hence, reference reflectors are essential for standardising the ultrasonic equipment and achieve a reference sensitivity level. The selection of type and size of the reflector are followed in accordance with the applicable code. Among the various reference reflectors used in ultrasonic testing, side drilled hole and notches are most commonly used. As per ASME Section V [7] code recommendation, ultrasonic testing operator selects Side Drilled Holes (SDH) for flat components and surface notches for curved structures like pipes and tubes. This is due to the difficulty in drilling SDH in curved components. This is practically possible for relatively bigger diameter and thicker jobs. For smaller diameter tubes, notch is used, because of variation in SDH depth from the surface of the tube when the measurement is made along the length of the SDH.

The sensitivity of inspection depends on the reflecting area of the reflector, that sends a portion of ultrasonic energy back to the probe. In general, the reflecting area of a side drilled hole is stringent than a notch, therefore they are preferred more than a notch. During the standardisation of equipment set up (Sensitivity calibration), the amount of energy reflected from a known sized reflector is set to a fixed height (typically 80% FSH) by adjusting the individual beam gain (gain offset) for each angle. For a good reflector, the reflected energy has to be proportionate to the beam path. Increase in beam path from lower angle to higher angle would have decreased in amplitude [6]. This decrease is due to increase in the travel path for higher angles which in turn causes increased attenuation in wedge and material.

Since Phased array sectorial beam sets produce multiple angles, the response of reflector to useful range of angles need to be studied to understand the uniformity in sensitivity. The various calibration processes involved in phased array inspection are **Velocity calibration**), **Wedge delay calibration**) **Sensitivity calibration** and **Time corrected gain calibration- TCG**. Therefore, it is decided to study the response of the reflectors for the range of beam angles, typically used for weld inspections.

**Experimental:**

To have a practical comparison of UT response between side drilled holes and surface notches, two samples are prepared from carbon steel material. Sample 1 is a 70 mm thick block that consists of 1.5 mm diameter side drilled hole at a depth of 25 mm (Figure 1). Sample 2 consists of four notches having various depths such as 0.5 mm, 1 mm, 2mm and 3 mm (Figure 2). The width of the notch is 5 mm and length of the notch is 25 mm. It is ensured that the SDH and surface notches are at same depth from the surface to have same beam travel in the material, which avoids need of performing TCG for this comparative study. Omni scan MX2 (32:128) equipment is used for the inspection trial. Phased array probe (5L64A12) of 5 MHz frequency with total elements of 64 and pitch of 0.6 mm is used. Shear wave wedge (SA12N55S-IHC) that has nominal refracted angle of 55 degrees (in steel) is used for the trial. Grease is used as a Couplant between the probe and wedge. Water is used as Couplant between the wedge and test samples. Sectorial group with active aperture of 16 is generated by using elements from 49 to 64. Shear wave beam set with angles ranging from 40 to 70 degrees is generated at 1-degree angle step.

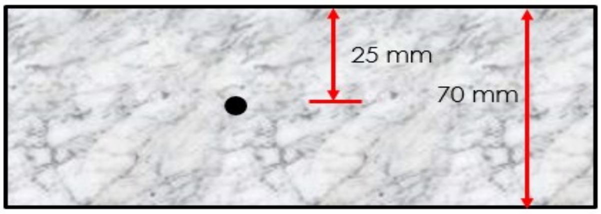


*Figure 1 Sample 1 with SDH reflector*


*Figure 2. Sample 2 with surface notch*

Velocity calibration is performed to determine the actual shear wave velocity in the material. Wedge delay and sensitivity calibrations are performed with side drilled holes present in the sample 1. After wedge delay calibration, the change in the beam delay for each angle is noted and after sensitivity calibration, the change in the gain offset for each angle is noted. The change in the beam delay and the gain offset for each angle are plotted (Figure 3 and Figure 4 ). Similarly, the wedge delay and sensitivity calibrations are performed for the sample 2 containing notches (0.5mm, 1mm, 2mm and 3mm depths).

## Results and discussion

### Beam delay and gain offset changes with the beam angles:

Figures 5 and 6 give plots between beam delay & beam angle and gain offset & beam angle, respectively. It is seen that the beam delay and gain offset increases almost linearly with the increase in the beam angle for the side drilled hole.

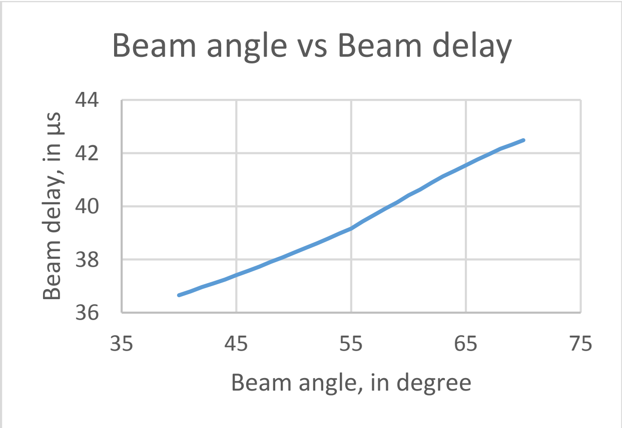


*Figure 3. SDH response for Wedge delay calibration*

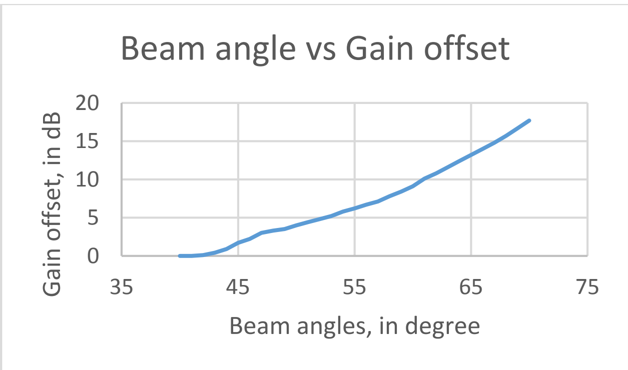


*Figure 4 SDH response for sensitivity calibration*

The beam delay and gain offset responses for a change in the beam angle for the notches are shown in the Figure 5 and Figure 6, respectively. It is observed that the beam delay exhibits linearity with the change in the beam angle, whereas gain offset shows linearity only up to certain angle (63°).

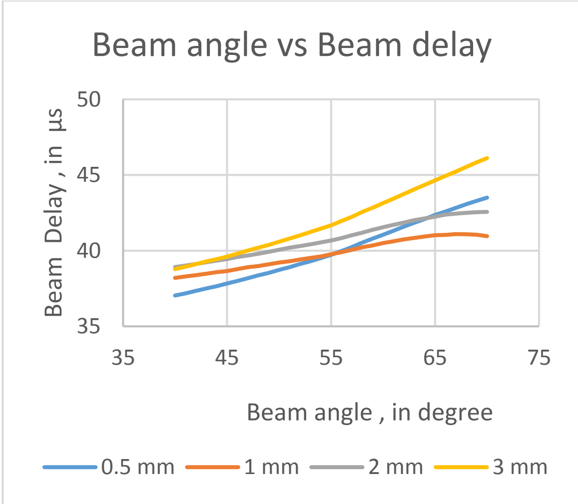


*Figure 5 Notch response for wedge delay calibration*

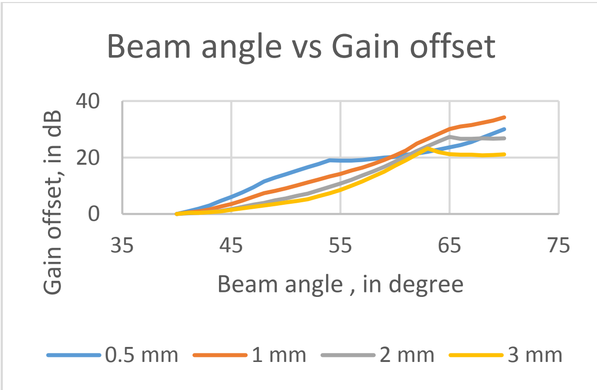


*Figure 6 Notch response for sensitivity calibration*

### Calibration of gain offset for side drilled holes:

While detecting a side drilled hole, higher angle takes longer path than the lower angles. This causes increased energy loss (due to attenuation and beam spread). The calibration process involves applying of increased gain offset to higher angles to bring all the angles to equal sensitivity level. For a side drilled hole calibration the loss of energy is uniform whereas for notch there is a variation in energy loss and subsequently variation in gain offset (particularly in the angles between 60 to 65 degrees).

To have a better understanding on the energy variation, the reflectors (SDH and notches) are scanned after making calibration. Since side drilled hole produces uniform sensitivity, it is used for calibrating the system and analyse the energy variation. The data acquired for 1.5 mm SDH is shown in *Figure 7*. It shows the different PAUT displays such as A, B and C scans.

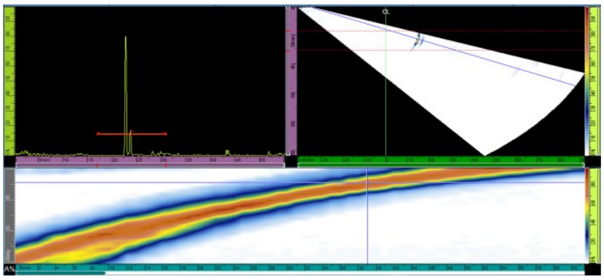

*Figure 7 Inspection of 1.5mm diameter SDH using SDH calibration*

The maximum amplitude obtained for each angle is observed and it is noted that all angles are getting reflected within the acceptable limit of 80% (uniform red colour shown in C scan). Since side drilled hole gives uniform sensitivity, same calibration is used to analyse the energy drop in notches. The notches of dimension 0.5 mm, 1 mm, 2 mm and 3 mm, are scanned perpendicular to the notch such that all the angles are getting reflected by the notch. The data acquired for the notches 0.5 mm and 1 mm is shown as Figure 8 and Figure 9. It is observed that the amplitude drops for the higher angles compared with the amplitude received for lower angles.

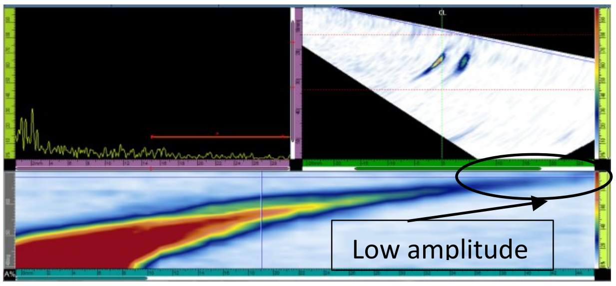


*Figure 8 Inspection of 0.5mm depth notch with SDH calibration*

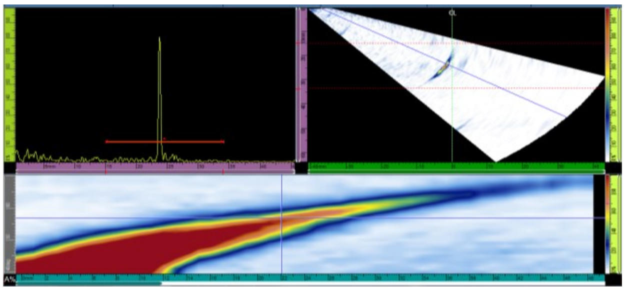

*Figure 9 Inspection of 1 mm depth notch with SDH calibration*

The data acquired for the notches 2 mm and 3 mm is shown in *Figure 10 and Figure 11*. It is noticed that the amplitude drops in the middle and it rises as the angle increases. To avoid saturation of signals, general gain is adjusted which applies the changes in all the angles.

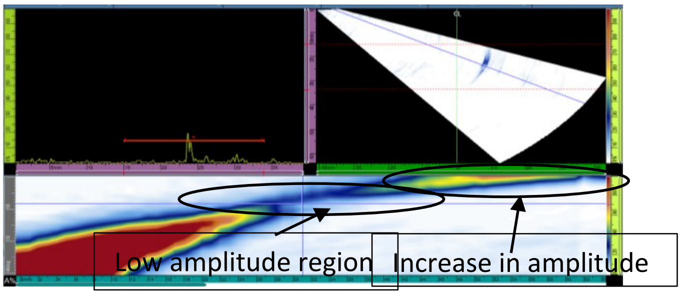


*Figure 10 Inspection of 2 mm depth notch with SDH calibration*

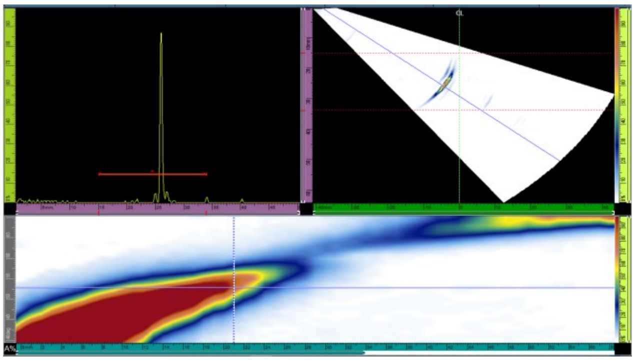

*Figure 11 Inspection of 3 mm depth notch with SDH calibration*

The maximum amplitudes obtained for all the angles for a 3 mm depth notch is detected and plotted *(Figure 12)*. The amplitude decreases with the increase in the beam angles up to 63° and then increases with further increase in the beam angles.

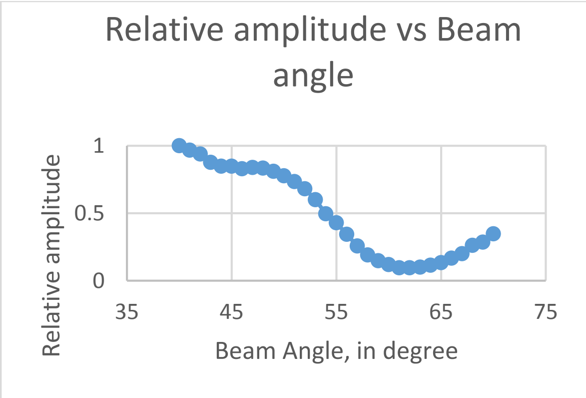


*Figure 12 Response of notch for SDH calibration sectorial beams*

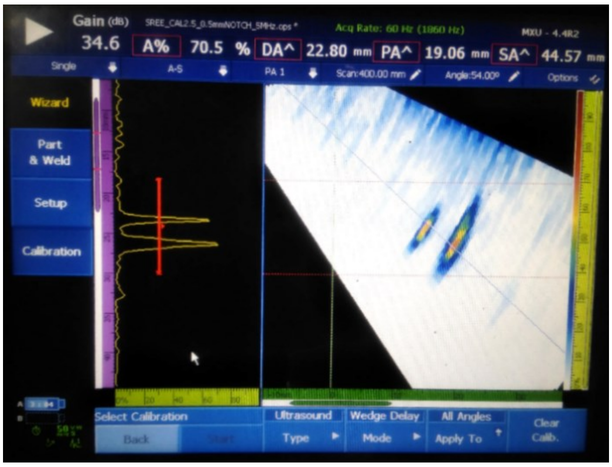


*Figure 15 Multiple reflections from notch*

**Simulation of notch response**

To validate the results, the inspection is simulated using CIVA simulation software. The experimental set up is modelled and an In-line scanning is done across a notch *(Figure 13)* such that all the angles will hit the notch reflector sequentially. It is observed that sound beam gets reflected by various portions of the notch. The similar responses are also evident during the practical trials as shown in the Figures 15, 16 and 17.

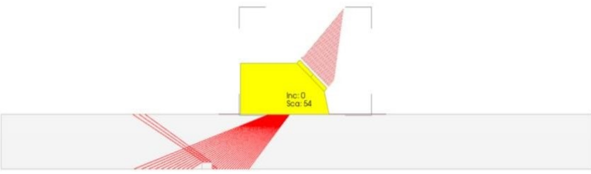

*Figure 13 In line scanning of notch in CIVA*

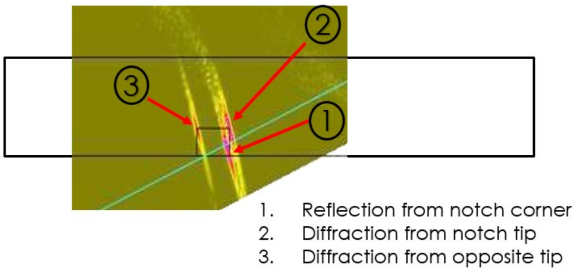


*Figure 14 CIVA Simulation for a notch reflecting surface*

It is noticed from the above results that the SDH gives uniform reflections, while the notch response is irregular between the angle 60 to 65 degrees. When the SDH is used for calibration purpose, the sensitivity obtained for all the angles looks uniform (Figure 4 and 9). The variation of gain offset for notches shows that energy reflected back to the probe is lesser for the beam angles between 60 to 65 degrees. This is because of reasons like mode conversion and multiple reflecting surfaces present in notch. The mode conversion takes place in the vertical wall of the notch for the angles between 60 to 65 degrees, causing reduction in the reflected energy. Multiple points such as bottom corner, top tip and opposite tip of the notches are causing reflection/diffraction from the notch. This is evident in CIVA simulation results and also in the practical trials (Figure 14 and 17).

The drop in energy from lower angles towards higher angles, for notch reflector (Figure 8 to Figure 12) reveal that the sensitivity is not uniform for all the angles when compared with uniform reflection of SDH (Figure 7). Figure 10 and 13 show that there is a drop in amplitude from 40 to 60 degree and it rises after 65 degree towards 70 degree. This shows that the loss of energy due to mode conversion is from 60 to 65 degrees. The drop in amplitude (relative to the maximum amplitude) of the reflected energy is up to 20 dB from 45 to 60 degree and it rises to around 11 dB for 70-degree beam angle.

**Conclusion:**

The study shows that side drilled hole is a good reference reflector for phased array inspection and notch will have irregular sensitivity. The variation in amplitude from the angle 45 to 60$^o$ is around 20 dB and the amplitude increase after 60 to 70$^o$ is around 11 dB. When a defect is detected by the angles between 60 to 65$^o$ (using notch as reference reflector), the sensitivity would be high for these angles compared with the lower angles.

The error in sensitivity is very high to an extent of 20 dB. This will cause a side wall lack of fusion or elongated slag to be sized with high sensitivity if detected in these angles range. This variation in sensitivity throughout the angles has to be taken care of during the interpretation, if notch is used as reference reflector where making a side drilled hole reflector is practically difficult. Such situations would arise while inspecting smaller diameter tubes/pipes where making a side drilled hole is difficult, the depth of the reflector from the surface will vary when measured at different lengths of the SDH.

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