Ultrasonic Simulation Studies for Sizing of Planar Flaws in Thick Carbon Steel Welds

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Abstract

Ultrasonic non-destructive testing typically involves detection of flaws that may affect the integrity of component under test. Once detected, the flaw is sized for its critical dimensions and its nature. The detection of flaw in the component by ultrasonic test is based on the principle of echo or reflection. Once the echo from a flaw is received, there are several approaches for analyzing the signal so that more and accurate information is obtained on the size of the flaw and its nature. The 6dB drop method is commonly used for sizing of flaws. This technique is based on determining the end points where the ultrasonic signal amplitude from the flaw drops to half of the peak amplitude. Though this method works well for large flaws whose size is larger than the beam width, it has a tendency to oversize the flaw which is smaller than the beam dimensions. In addition to beam divergence, flaw sizing also depends upon the orientation of the flaw with respect to incident sound beam.

Two different angle beam probes are commonly used for ultrasonic inspection of thick welds. Simulation studies were carried out to understand the effect of beam divergence and flaw orientation on sizing of planar flaws using 45 & 60 deg probes. During simulation study the flaws of different orientations and sizes present at different depths from the scanning surface are introduced in a thick block. Signal amplitude from these flaws with respect to reference and their 6 dB sizes from the B-scan image are obtained. The flaws are also sized by tip diffraction techniques. A methodology to be adopted for sizing crack like flaws in thick sections is formulated based on the simulation results. The paper describes the results of simulation studies on ultrasonic response from planar flaws of various orientations, their imaging and the methodology to be adopted for their accurate depth sizing. The paper also describes the experimental results to validate the flaw sizing approach.

1.0 INTRODUCTION

Ultrasonic examination is one of the most commonly used volumetric Non-Destructive Examination techniques for defect detection in weld joints.Once detected, the flaw is sized for its critical dimensions and its nature. Minimum two different angle beams are used for carrying out weld inspection. This widely used approach is good enough for defect detection, however, due to beam divergence effects sizing of defects may not be accurate. Defects oriented perpendicular to sound beam and greater than the beam size can only be accurately sized by the widely used 6dB drop technique. Defects which are smaller than the beam size or which are not oriented perpendicular to the sound beam are oversized when sized by 6dB drop technique. In the present study efforts have been made to understand the effect of beam divergence, flaw size and flaw orientation on defect sizing. A methodology to be adopted for sizing crack like flaws in thick sections is formulated based on the simulation results.

2.0 BEAM DIVERGENCE

The sound beam spreads as it travels inside the material. This phenomena is usually is referred to as beam divergence. This factor primarily depends upon diameter of the crystal and wavelength. Beam Divergence is defined as follows:

$$\sin \theta = k\, \lambda / D \quad [2]$$

Where,
θ = half beam divergence angle
λ = wavelength of ultrasound
D = Diameter of crystal of the probe
k = Factor depending upon how the boundary of sound beam is defined i.e, whether 6dB, 10dB etc.

Because of the beam divergence effect, the length and the through wall depth of the flaw are oversized using amplitude based sizing technique. The beam divergence increases with the sound path in the material. As a result, if the same flaw is detected by 45^o& 60^o probes, the spread of the indication and the size estimated from this spread will be higher by 60^o Probe (higher beam path) as compared to 45^o probe.

3.0 6dB DROP METHOD FOR DEFECT HEIGHT ESTIMATION& EFFECT OF BEAM DIVERGENCE

6dB drop technique is amplitude based sizing technique, which is widely used in industries. This technique is based on determining the end points where the ultrasonic signal amplitude from the flaw drops to half of the peak amplitude. Though this method works for the large flaws whose size is larger than the beam width, it has a tendency to oversize the flaw which is smaller than the beam dimensions.

Simulation studies were carried out in which two defects having heights 3 mm (smaller than beam width) and 24 mm (larger than beam width) and orientation favorable for a 45° probe were introduced in a 140 mm thick carbon steel block at three different depths viz. 40 mm, 80 mm and 120 mm. Table-1 below gives the 6dB spread of these defects at various depths as obtained by simulation. The spread of 3 mm size defect is very large relative to its actual size. This is because of the beam divergence effect. Moreover the spread is more for a defect located at higher depth, because beam width increases as it travels in the material. However, for 24 mm defect which is higher than the beam width, the 6dB spread is equal to its actual size.

Table 1: 6dB Sizes of Planar defects as obtained by simulation

Depth from ID surface (mm)	6dB Size (mm) [Actual Height = 3mm]	6dB Size (mm) [Actual Height = 24mm]
40	8.5	24
80	10.6	24
120	14.8	24

In order to assess the accuracy of depth assessment of flaws obtained by 6dB drop method by 45^o and 60^o probe, experimental studies were carried out on the reference block with side drilled holes (simulating volumetric flaw) and inclined slots (simulating planar flaws). Table 2 gives the results of depth assessment obtained on SDHs using 45^o& 60^o probes.

Table 2: Results of depth assessment obtained on side drilled hole

Probe Angle (degrees)	Depth from ID surface (mm)	Actual size (mm)	Size by 6 dB drop method (mm)
45	32	6	9
45	65	6	7
45	96	6	15
60	32	6	8
60	65	6	10
60	96	6	15

Table 2 indicates that with both 45^o and 60^o shear wave probes, the flaw size evaluated is more than the actual. Table-3 gives the results of the depth assessment on inclined slots at various depths using 60^o shear wave probe.

Table 3: Results of depth assessment obtained on inclined slots using 60^{o}probe

Location from surface (mm)	Orientation (degrees)	Actual height (mm)	Height by 6 dB drop method (mm)
10	6	6	6
30	6	6	9
70	6	6	11
30	20	10	23

The results indicate that the 6 mm height flaw is measured accurately at 10 mm depth and oversized at higher depths because of beam divergence effect. To study the accuracy of sizing of flaws by 6dB drop method, simulation studies were carried out using CIVA 11 software on the 140 mm thick carbon steel block. Three planar flaws having height of 6 mm, 12 mm and 18 mm were introduced in a sample. These flaws were oriented at 45^o to the surface normal and were located at a depth of 100 mm from the scanning surface. The schematic of the simulation configuration is shown in the following figure:

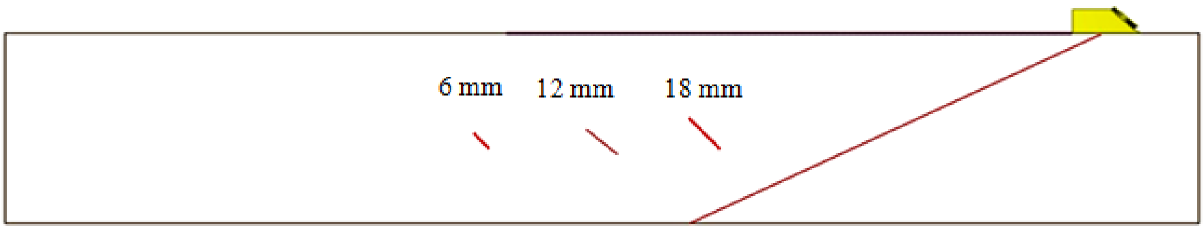
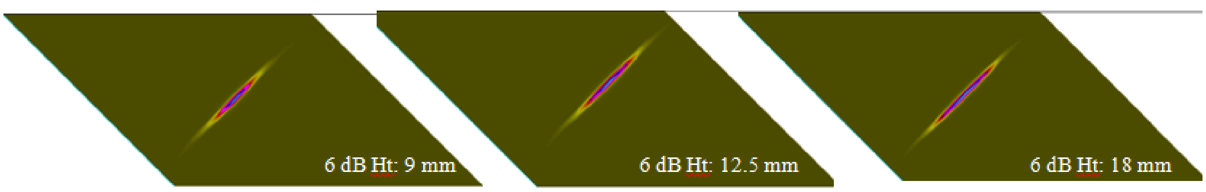


Figure-1: Schematic of Carbon Steel block used during simulation studies



(a) (b) (c)

Figure-2: B-Scan results for 45^o inclined slot with through wall height of (a) 6 mm (b) 12 mm and (c) 18 mm

The defect response of the simulation exercise is shown in Fig-2, which shows the B-Scan image from simulated planar flaw of different depths. The 6dB depth estimate was made for these three flaws from the corrected B-Scan images. The results indicated that the 12 mm and 18 mm height flaw are sized accurately by 6dB drop method, while 6 mm height flaw is oversized to 9 mm as the beam width at this location is larger than 6 mm. This study indicates that a 6dB estimate of flaw height is accurate provided that the flaw is oriented perpendicular to the sound beam and the flaw size is equal to or greater than the beam width at that location.

4.0 EFFECT OF FLAW ORIENTATION ON SIGNAL AMPLITUDE AND SIZING

In order to understand the effect of flaw orientation on the signal amplitude, simulation studies were carried out. During this study, the planar flaws having different height (6, 12, 18 & 24) and orientations (0^o to 70^o) was introduced at three different depths from scanning surface viz. 40 mm, 80 mm and 100mm in the virtual component of 140 mm thickness as shown in Fig-3. The variation of signal amplitude with flaw orientation using 45^o and 60^o probes is shown in Fig-4. The signal amplitude obtained from these flaws is normalized against the signal amplitude obtained from 6 mm SDH located at same depth as other flaws.

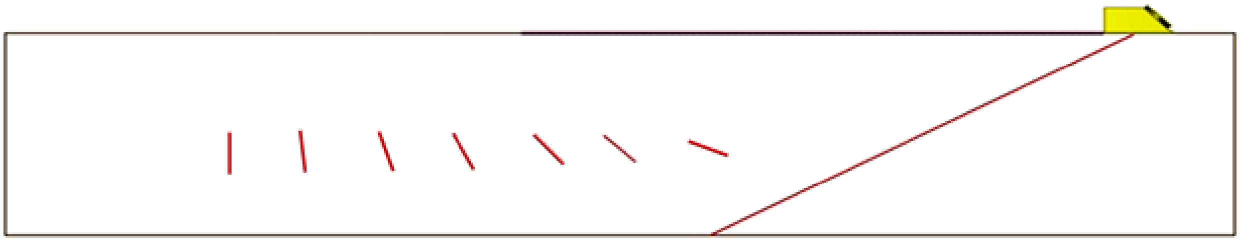


Figure-3: Virtual component with notches at different orientations

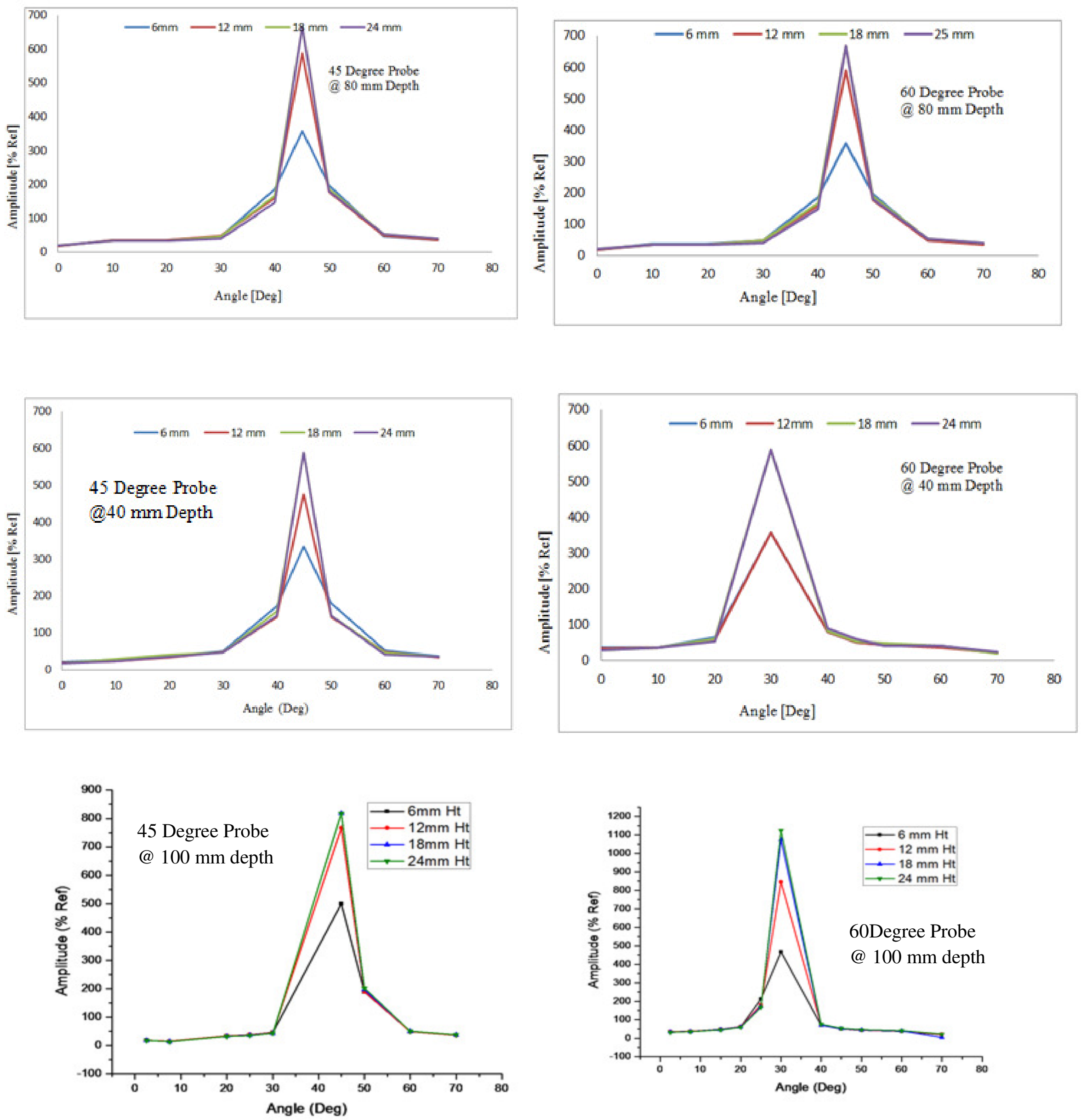


Figure-4: Variation of signal amplitude with flaw orientation for 45^o Probe & 60^o Probe @ various depths

The results shows that the signal amplitude from flaw is more than 300 % of reference even for the flaw of 6 mm height, if the flaw is perpendicularly oriented towards the sound beam (45^o slot for 45^o probe and 30^o slot for 60^o probe). For the planar flaws which are unfavorably oriented towards the sound beam, the signal amplitude drops to less than 100 % of reference. In order to study the effect of flaw orientation on imaging of flaws, simulation studies were carried out on a 140 mm block. Flaws having 12 mm height, but different orientations (2.5°, 20°, 40°, 45°, 50° and 70°) with respect to the normal were introduced in the block. The simulation results using a 45° shear wave probe are shown in Figure-5.

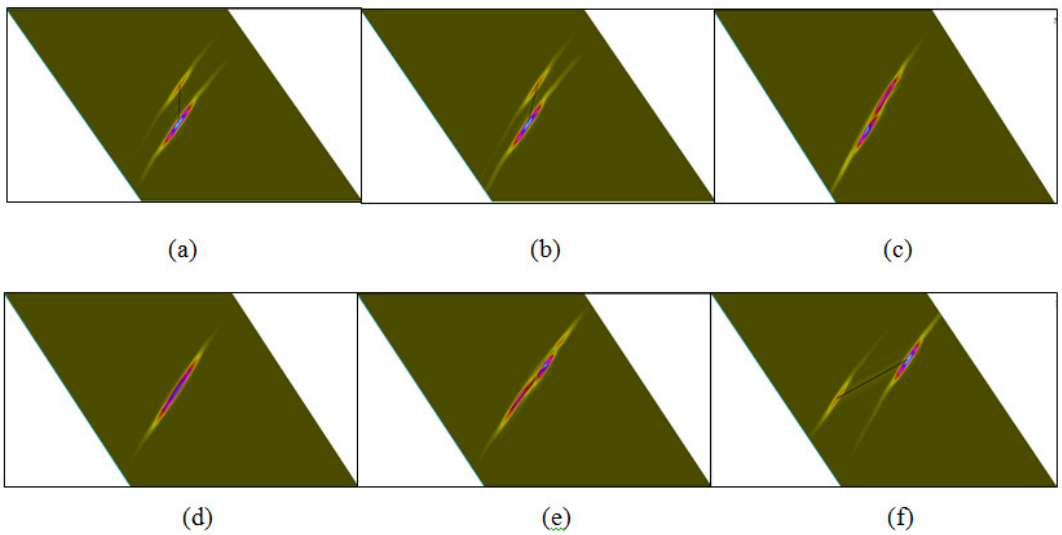


Figure 5:B-scan image of slot having 12 mm height and oriented at (a) 2.5^o(b) 20^o (c) 40^o (d) 45^o (e) 50^o and (c) 70^o

The results indicate the following:

- Flaw oriented at 45° (perpendicular to the sound beam): High amplitude signal from the face of the flaw is obtained
- Flaw oriented at orientations close to 45° (40° and 50°): Two signals merging with each other are seen.
- Flaw oriented at lower angles (away from normal incidence): Distinct signals from upper and lower tips are seen.
- Flaw oriented at higher angles (away from normal incidence): Distinct signals from upper and lower tips are seen.

For mis-oriented flaws we obtain signals from the tip rather than face signal. Figure-7 below give the variation in ratio of amplitudes from top and bottom tip of the flaw with respect to the orientation of the flaw.

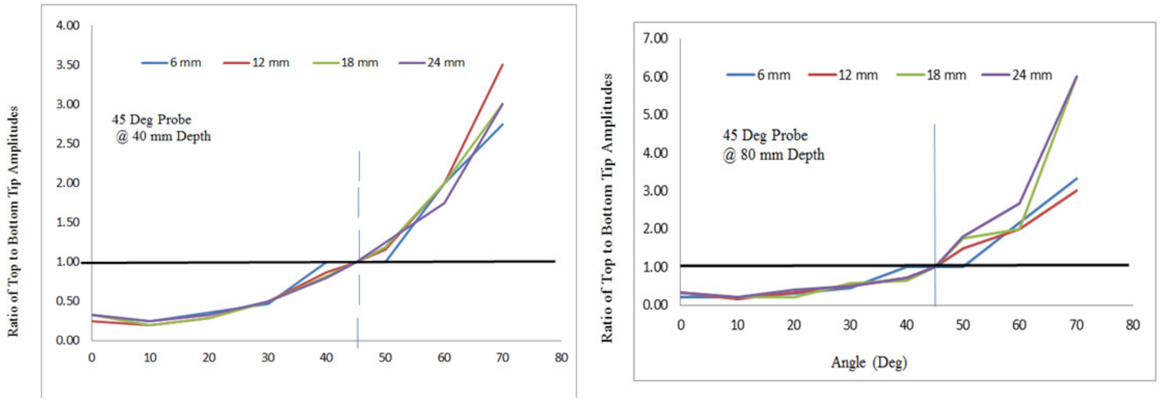


Fig 7: Variation of Ratio of Top Tip to Bottom Tip Amplitudes with respect to orientation

From the above figure it can be concluded that for planar flaw orientation < beam angle, the ratio of top tip amplitude to bottom tip amplitude is < 1 and vice versa. Further, for orientation less than beam angle, the ratio decreases as the flaw becomes more and more unfavorably oriented. Whereas for flaw orientation > beam angle, the ratio increases as the flaw becomes more and more unfavorably oriented.

The depth sizing of flaws oriented at different angles (from simulation results) using 45^{o} shear wave probe are carried out by 6 dB drop technique and results are shown in Table 4.

Table 4: Sizing of flaws by 6 dB drop method by 45 deg. shear wave probe

S.No	Flaw orientation (degrees)	Actual Height (mm)	Flaw height by 6 dB method (mm)
1	2.5	12	10
2	20	12	10
3	40	12	17
4	45	12	12
5	50	12	14
6	70	12	8

The results indicate the following:

- Flaw oriented at 45° (perpendicular to the sound beam): Sizing by 6dB drop method is very accurate
- Flaw oriented at orientations close to 45° (40° and 50°): Flaw height is over estimated since the signals from upper and lower tips of the flaw merge with each other
- Flaw oriented at lower and higher angles (away from normal incidence: 2.5°, 20° and 70°): Flaw height is under estimated since the height is measured from one of the tip signals only, as the signal from other tip has amplitude less than 6 dB of the upper tip signal. In reality, if two signals, one with higher amplitude and other with lower

amplitude is obtained, then while using 6 dB drop method, two separate flaws will be reported.

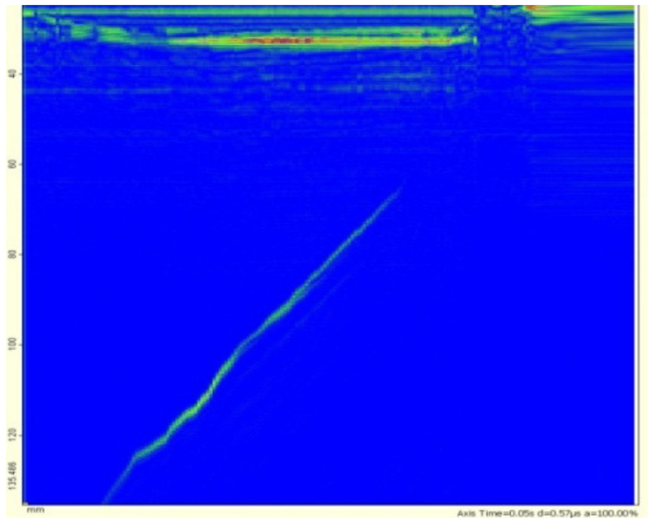


Figure:B-scan image obtained by 60° probe

To study this effect of flaw orientation on depth sizing using 6 dB drop method, ultrasonic examination was carried out on 60 mm thick stainless steel block having 10 mm height, 20° oriented inclined slot present at a depth of 30 mm from surface. B-scan obtained from this flaw is shown in Figure 8.

B-scan image shows only a single long signal, due to the merging of upper and lower tip signal. As observed during the simulation exercise, the signals have merged since the sound beam is almost at normal incidence to the flaw surface. From the image, the 10 mm height flaw is imaged as 23 mm by 6 dB drop technique. From these results, it is clear that 6dB drop technique oversize the flaw height, when the flaw is slightly unfavorably oriented to sound beam.

In the inspection data, if two signals separated depth-wise are seen, then it indicates that the flaw is oriented away from the normal incidence. In such case, it is prudent to evaluate the height of the flaw by finding out the location of the upper and lower tip, instead of treating these two signals as two separate flaw indication and estimating their height by 6 dB drop method.

5.0 FLAW SIZING BY TIP DIFFRACTION TECHNIQUE

The sharp tip of a well-defined internal defect like a crack will diffract an incident ultrasonic beam, creating a spherical wave front whose arrival at the probe can be used to locate the tip and measure the depth of the crack. To understand this effect, the simulation study was carried out on 140 mm thick carbon steel block, having simulated planar flaws oriented at 2.5°, 20°, 45° and 55°. The B-scan obtained with 45° probe during this simulation study is shown in Figure 9.

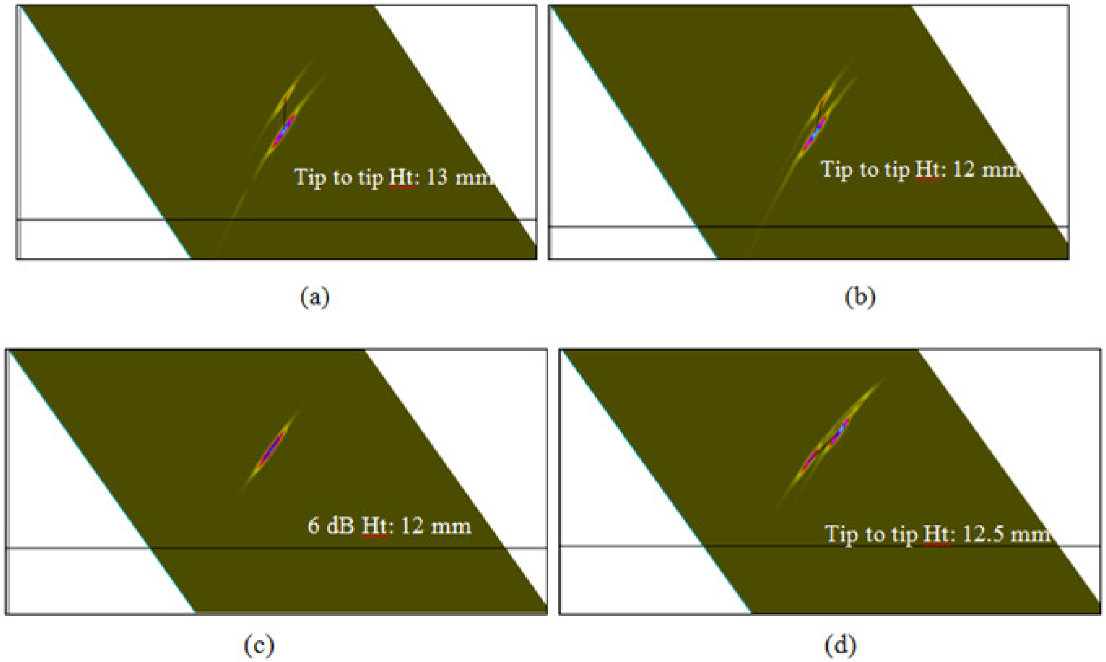


Figure-9: B-Scan image of slot having 12 mm height and oriented at (a) 2.5^o (b) 20^o (c) $45^o$and (d) 55^o

Except for the flaw which is oriented at 45 deg. all the flaws show distinct upper and lower tip signals. The flaw height evaluated by tip diffraction method is very close to the actual value. In order to verify the effectiveness of tip diffraction method, experiments were conducted on 60 mm thick stainless steel block having 10 mm height slot, oriented at 0 deg. (normal to the surface). The B-scan images of this slot using 45^o and 60^o probes are shown in Figure 10.

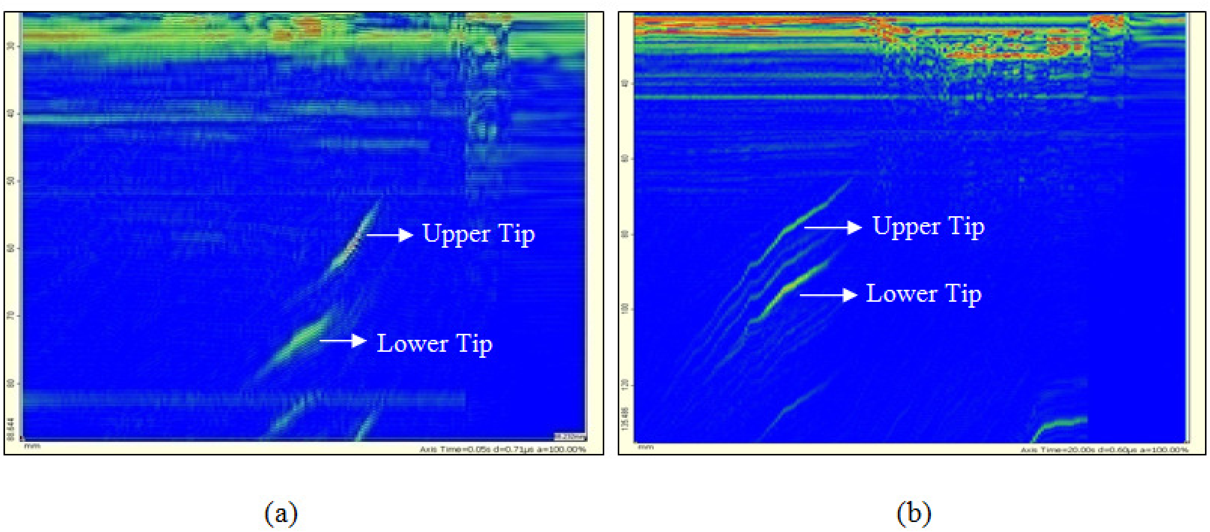


Figure 10: B-Scan Images of 0^o slot (a) 45^o (b) 60^o

The above images show distinct upper and lower tip signals using both the probes. The flaw height assessed by tip diffraction is found to be very close to the actual value.

6.0 EFFECT OF FLAW SIZE

In order to study the effect of flaw size, three different types of simulation studies were carried out:

(a) Flaws oriented favorably to sound beam (45° Probe)- Flaws of different sizes viz 6mm, 12mm 18 mm and 24 mm were introduced at a given depth from the scanning surface (100 mm in this case) and variation in amplitude and their 6dB sizes was studied. Table-5 below gives the result of the simulation. From Table-5 it can be inferred that defects with size > beam width can be accurately sized by 6dB method. Whereas defects having size less than beam width are oversized. For, sizing of such kind of flaws amplitude look-up tables are proposed in 7.0.

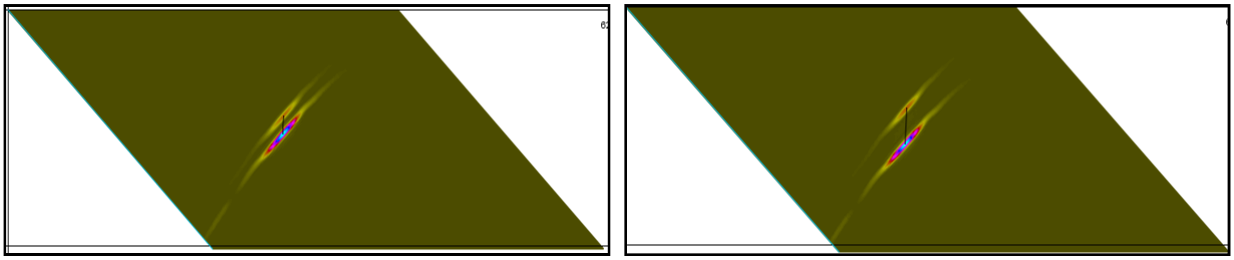
(b) Flaws largely mis-oriented to sound beam (45° Probe)- Flaws of 0° orientation and sizes viz 6mm, 12mm, 18mm and 24 mm were introduced at a given depth (100 mm in this case) from the scanning surface and variation in imaging and tip-to-tip sizes was studied.Table-5 below gives the result of the simulation. It was observed that for largely mis-oriented flaws the two tips are seen separate and Tip-to-Tip sizing is fairly accurate.

(c) Flaws slightly mis-oriented to sound beam (45° Probe)- Flaws of 40° orientation and sizes viz 6mm, 12mm, 18mm and 24 mm were introduced at a given depth (100 mm in this case) from the scanning surface and variation in imaging and tip-to-tip sizes was studied.Table-5 below gives the result of the simulation. For slightly mis-oriented planr flaws Tip-to-Tip sizing is fairly accurate when defect size is greater than beam size. For defects having sizes less than beam width two tips get merged. Smaller the defect size more profound is the merging. Hence, for very small planar flaws tip to tip sizing may not be possible.

Table 5: Effect of Flaw Size

Actual Defect Size [mm]	Favourable Orientation		Largely Mis-Oriented [0^o]	Slightly Mis-Oriented [40^o]
	Amplitude [% FSH]	6dB Size	Tip-to-Tip Size [mm][	Tip-to-Tip Size [mm]
24	100	24	22	22
18	96	18	16	16
12	83	14	10	10
6	49	13	6	Tips merged

Figure 11 shows the B-scan image for a flaw having depth of 6 mm and 12 mm oriented at 2.5° using a 45^o shear wave probe. While 12 mm flaw shows distinct tip signals, these signals almost merge with each other for a 6 mm flaw. This indicates that if the flaw has lesser depth, the upper and lower tip signals may not be seen separately, even if the flaw is oriented unfavorably to the incident sound beam.



(a)(b)

Figure 11: B-scan image of slot oriented at 2.5° having through-wall height of (a) 6 mm and (b) 12 mm

7.0 METHODOLOGY TO BE ADOPTED FOR SIZING OF PLANAR FLAW

The methodology presented here for sizing of planar flaw is based on following assumptions:

1. B-Scans of the scanning zone are recorded and available
2. SDH is used as reference defect.

Depending on the location, orientation and size of the planar flaw, one of the following three types of signals will appear in B-Scan:

1. A single signal from face of the flaw.
2. Two separated signals
3. Two merged signals.

(1) *Single Signal:* Signal from the face of the planar flaw will be obtained only if it is oriented perpendicular to the sound beam. This can be identified by its amplitude. The amplitude when normalized with respect to reference defect shall be greater than 100 %. Now in order to size the defect we make use of *"Look-up Tables"* prepared by pure simulation studies for a given probe and given material. For illustration one such look up table is given below:

Table-6: 6dB Size Look-up Table

Probe- 45° Shear Wave			
Location of Defect from Scanning Surface (mm)	H1	H2	H3
	6 dB sizes as obtained from simulation for flaw of height H1	6 dB sizes as obtained from simulation for flaw of height H2	6 dB sizes as obtained from simulation for flaw of height H3
D1	A1	A4	A7
D2	A2	A5	A8
D3	A3	A6	A9

However, defects having height less than or equal to the beam width will be sized equal to beam width. Such kind of planar defects can be sized on the basis of their amplitudes. This calls for another "Look-up Table" Table-7.

Table-7: Amplitude Look-up Table

Probe- 45^o Shear Wave			
Location of Defect from Scanning Surface (mm)	H1	H2	H3
	Amplitude as obtained from simulation for flaw of height H1	Amplitude as obtained from simulation for flaw of height H2	Amplitude as obtained from simulation for flaw of height H3
D1	B1	B4	B7
D2	B2	B5	B8
D3	B3	B6	B9

(2) *Two Separated Tip Signals:* when two separate signals are obtained there can be two possibilities:
   (a) There are two separate defects. However, in this case each shall have normalized amplitude greater than 100 %. If it is so, then the indications are sized as explained in (1) above.
   (b) Signal from top and bottom tip of the same defect. In this case tip to tip sizing shall be done.

(3) *Two Merged Tip Signals:* This is obtained in case the defect is slightly mis-oriented from favorable orientation. Over the span of signal in B scan if we move from one end to another, the amplitude will first increase to a maximum value (1st peak) and then decreases and then again increases to some value (2nd Peak), after which it falls gradually. Defect can be sized by measuring Peak to Peak distance in corrected B-Scan. Also from the ratio of amplitude of top tip to bottom tip, orientation of the flaw can be inferred.

8.0 REFERENCES

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