Comparison of Detection and Height Sizing Ability of Planar Defect in Thick Wall Weld Steel Between PAUT and TOFD Techniques

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Abstract: Pressure vessels with thick wall steel materials in-service used in Refinery industries generally suffers potential failures from planar defects, then they must be strictly inspected by Law and Standards throughout their life cycle to guarantee for safe operation. This research aims to compare the detection ability and height sizing accuracy of Phased array ultrasonic testing (PAUT) and Time of flight diffraction (TOFD) methods in order to determine which technique is more suitable for detection and height sizing small planar defects. Three flaw sizes were mocked up around the acceptable size of ASME Section VIII Division 2 Code, which are at smaller acceptable size, at rejected size and over the rejected size for both on surface and under surface respectively. The results show that for the Small under surface planar defects, TOFD is better than tip back diffraction technique of PAUT in detection and height sizing. TOFD is also able to size smaller defects. Defects high under 5 mm. are not blind in TOFD method whereas it is not clearly distinguished by tip back diffraction technique and lead to easily misinterpretation. For Surface planar defects, tip back diffraction technique exhibits similar accuracy results compared to TOFD and can also size small defects. Tip back diffraction technique trends to provide the undersize, especially defects at surfaces because of the broad saturated signal area. Moreover, PAUT should not be used as a stand-alone scanning technique, in case of requiring high reliability on height sizing such as Fitness-for-service calculation or Engineering Critical Assessment (ECA) analysis and a combination of PAUT and TOFD is recommended.

Keywords: Ultrasonic testing (UT), Phased array ultrasonic testing (PAUT), Time of flight diffraction (TOFD), Planar defect, Height sizing. Tip back diffraction, Pressure vessel.

1. Introduction

Pressure vessels with thick wall steel materials have been used in Refinery industries undergo both operation changes and hydrocarbon environments or sour service while in-service [1]. These steel pressure vessels operate in low to ambient temperatures with hydrocarbon environments or sour service. The design temperature for steel pressure vessel materials typically range from -48 C to AMB. The welding of these thick wall steels [2-3] during maintenance activities or prolonged exposure of the steel to hydrocarbon or sour service conditions can be leading to deleterious effects such as embrittlement or loss of toughness. Hence, vessels constructed with the thick wall carbon steels, cracking triggered by ductile-to-brittle transition temperature region, unwanted brittle microstructures [4] or hydrogen diffusion [5] into the heat effected zone (HAZ) coinciding with high residual stresses, represents a potentially catastrophic failure.

For decades, Radiographic Testing (RT) has been applied as the primary NDE method to examine and evaluate the thick wall steel pressure vessel condition during equipment Shutdown and Major Turnaround Projects which most of the time its period has been relatively short in order to minimize the downtime cost. But main disadvantages of radiography (RT) are time consuming, costly and potential hazard to health associated with the ionizing radiations which are the basis of RT method. Currently, Ultrasonic Test (UT) as an alternative method to radiography [6-8], has been accepted and widely applied for in-serviced pressure vessel inspection in industries. Furthermore, ASME Section VIII Div. 1 & 2 [6] and Local Law & Regulations [8] have been accepting these two UT techniques including phased array ultrasonic test (PAUT) and time-of-flight diffraction (TOFD) in replacing the conventional radiography (RT) method for welding inspection of steel pressure vessels.

Acceptance criteria [9-10] for planar defects (e.g. cracks or lack of side wall fusion) of these 2 UT techniques based on the fundamental principle of fracture mechanic which requires knowing the accurate data on defect size/dimension for acceptance or rejection consideration. Therefore, the selection of a proper UT technique in detection and sizing the flaw dimension is very essential. A minor error in flaw detection and sizing can be leading to wrong judgment and can cause for catastrophic failure on equipment during in service. Anmol Birring [11], there are numerous UT techniques in detection, determining and sizing planar defects such as Amplitude

ratio, dB drop likes 6 dB or 20 dB drops, and tip diffraction techniques likes TOFD and Tip back diffraction [12].

Many years, PAUT has been most popular and widely used for planar defect detection and sizing that applicable for steel pressure vessel inspection but however there had been many cases in the past found that inspection results reported by PAUT were questioned and it could not be used as a reference for Fitness-For-Service (FFS) calculations or Engineering Critical Assessment (ECA) analysis. Currently, there is higher potential and demanding to use TOFD in replacing PAUT and RT for thick weld steel pressure vessel inspection because it is another UT method that has been accepted by Standards for the Statutory Inspection and in applying FFS and ECA analysis which requires the high reliability of UT method.

Recent studies [12,13,14,15,16,17] concluded that sizing accuracy by amplitude-drop was not good enough and generally inadequate for Fitness – For - Service (FFS) calculation. Olympus NDT [13], sizing should be performed and based on non-amplitude (time- of-flight-diffraction) technique in case of Fitness-For-Service Propose or Engineering Critical Assessment (ECA) analysis. TOFD has provided the most accurate results in measuring and determining the sizing of different types of planar defects with its accuracy (±0.3 mm) [13]. However [13-14], TOFD success relies on many set-up parameters and TOFD should not be stand-alone quick scanning UT method. TOFD is somewhat difficult to interpret and has some limitations for surface open defects due to dead zones or having poor resolution for some significant small defects and some planar defects were not be detected (high as 3 mm and 5 mm) with sizing accuracy is low as ±4 mm [13,15] which are very concern for in-service thick wall pressure vessel inspection that some planar defect likes fatigue cracking and hydrogen induced cracking are potentially started from small flaw and connected to steel surface.

Olympus NDT [13], how dose PAUT fit for FFS and ECA concept of safety case, monitoring, and disposition compare with TOFD? PAUT has specific advantages compare with TOFD; focused beam with high signal to noise ratio (SRN), interpretation easy and straightforward, multiple beam with high resolution, data analysis is significant easier than for TOFD, and data can be plotted in 2D/3D for analysis. PAUT using tip back diffraction technique can size to similar accuracies to TOFD, sizing accuracy ~0.5 mm though careful practices [12] and can size smaller planar defect. However, a reliable planar defects sizing based on tip-echo techniques of PAUT method depends on a suitable specimen thickness, phase array probe frequency, damping, and bandwidths as well as material quality [13]. Tip back diffraction technique, height sizing can be done by simply measuring the vertical distance between the images of the peak amplitude from diffracted echoes. Measuring the distance between tip to tip echoes has provided the high accuracy, but however measuring the distance between tip to reflect peak echo from a defect corner is potential to provide less reliable and accuracy, especially in case of small open planar defects. In practice, small flaw sizes can be easily overestimated by several millimeters [13] and these also can have a very deleterious impact on the inspection results.

Therefore, it is unclear if tip diffraction technique such as PAUT by tip back diffraction and TOFD is applicable for small planar defects, especially small open planar defects on surfaces [19-22]. Some blinded defects (high as below 5 mm) with sizing accuracy is low as formerly mentioned by TOFD technique [13,15] will be studied and compared with tip back diffraction technique of PAUT and if only stand-alone PAUT method is still enough to provide the satisfactory accuracy result for FFS and ECA analysis which requires very high reliability of UT height sizing method.

This paper covers the work performed on a detailed study comparing the accuracy in detection and high sizing ability for planar defects in thick wall weld steel between PAUT and TOFD. Three flaw sizes were mocked up around the acceptable size of ASME Section VIII Division 2 Code, which are at smaller acceptable size, at rejected size and over the rejected size for both surfaces and subsurface. The objective is to determine which UT technique is more suitable in detection and height sizing planar defects, especially small open planar defects on surfaces of thick weld steel and this research result can be benefit for industries in selection of proper UT techniques for the Statutory Inspection as LAW and for the planar defect height sizing and growth monitoring for Fitness-For-Service (FFS) calculations or Engineering Critical Assessment (ECA) analysis.

2. Theories

2.1 Planar defects and acceptance criteria [7,9,23].

Flaw types in a weld are categorized into two major types including planar and volumetric defects. Because planar defects as per ASME Section VIII Div.1 UG Appendix 12 [7] such as cracks and lack of side wall fusion (LF) are more harmful and come with higher risks than volumetric defects, thereby in-service equipment inspection has been mostly focused on planar defects. Fracture Mechanic's theory refers to a vital specialization within solid mechanics in which the presence of defects was assumed. Defects can be voids, dents on the surface or internal pores. Fractures are typically initiated at tip of the planar defect; stress is concentrated at the tip of the defects under the loads and propagates catastrophically through the structure. Crack tip parameter describes the severity of a failure by showing the ability of a material to resist a fracture. To study the size of a defect (a) and

stress under the load (σ) affected to the fracture, it can be formulated in the expression for stress intensity factor (K) as follow:

$$K1 = Y\sigma\sqrt{\pi a} \qquad (1)$$

Written as:
K1: Stress intensity factor, K1C: Stress intensity factor at critical stress

Material can resist a fracture when K1 is less than K1C. This property is called fracture toughness. Both PAUT and TOFD techniques are mainly applied in the principle of UT requirements for fracture-mechanics based acceptance criteria as per ASME Section V Article 4, MANDATORY APPENDIX IX [9] by considering flaw through-wall dimension and the length of flaw. These values are determined for using in the flaw rejection or acceptance. Therefore, the selection of a proper UT technique in detection and determining flaw dimensions is very essential for this concept. Minor errors in flaw sizing could be leading to wrong judgment and decision and could be causing for catastrophic failure on equipment during in service.

2.2 NDE Methods.
2.2.1 Phased Array Ultrasonic Testing (PAUT) [13-14, 24]

Phased array ultrasonic technology was adapted from the medical field to the industrial sector at the beginning of the 1980s. By the mid of 1980s, piezocomposite materials were developed and made available to manufacture the complex-shaped phase array probes. Phased array ultrasonic testing (PAUT) is an advanced UT method. The term *phased* refers to the timing, while the term *array* refers to the multiple elements as illustrated in *Figure 1*. A phased array system utilizes the wave physics principle of phasing. It varies the time between a series of outgoing ultrasonic pulses in such a way that the individual wave fronts generated by each element in the array combine with each other. This action adds or cancels energy in a predictable way that effectively steers and shapes the sound beam. This is accomplished by pulsing the individual probe elements at slightly different times. The numbers of elements in a probe can be 8, 16, 32, 64 and 128. Each piezoelectric element in the probe is adjusted (focal lows) by computer-controlled excitation. Elements are pulsed into groups of 4 to 32 elements in order to improve effective sensitivity by increasing aperture, which then reduces unwanted beam spreading and enables shaper focusing. A probe can be focused and swept the beams at 45 to 75 degrees electronically without moving. The PAUT probe can spread signal emissions across a wider range of frequencies, allowing a wider area of coverage. Data from multiple beams is combined to create a visual image such as A scan, B scan, C scan, D scan and S scan as *in Figure 2*. The PAUT display is in 2D or 3D, allowing the operator to see the flaw location and measure its size.
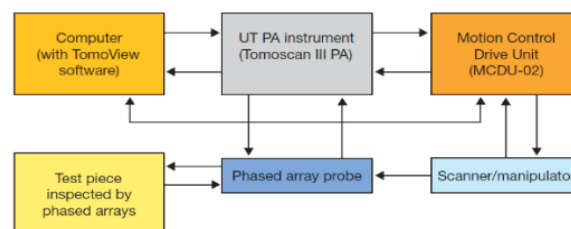
Figure 1: Basic components of a phased array system [14]
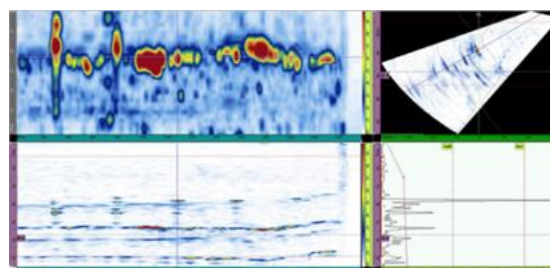
Figure 2: Example of PAUT display; A Scan, B Scan, C Scan and S Scan

2.2.2 Time of Flight Diffraction (TOFD) [13-14,25]

Time of flight diffraction is an advanced method of UT. TOFD technique is based on the diffraction of ultrasonic waves from the tips or edges of flaw as *shown in Figure 3*. It is different from UT and PAUT which are based on the signal amplitude reflection from the interface of flaw [24]. TOFD usually uses longitudinal waves for the primary detection. In addition to energies diffracted by defects, the TOFD method will also detect a surface (lateral) wave traveling directly between the probes and also a back-wall reflection from energies that reach the back of the test piece. Defects on the upper and lower surfaces are difficult to detect due to the dead zone in the lateral wave and because of the dead zone in the back-wall signal.
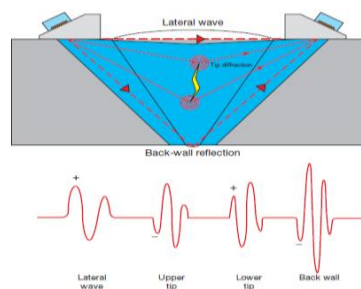
Figure 3: Principle of Time of Flight Diffraction (TOFD) [14]

TOFD uses 2 probes (Transmitter and Receiver) placed on each side of the weld. A *transmitter* sends the ultrasonic beam into the material. When beam comes into contact with the tip of a flaw or crack, it is diffracted, and energy is sent to the *receiver*. The flaw is the signals between the lateral wave and back wall echo, as shown in *Figure 3*. TOFD can detect and recode a signal diffracted from defect tips for both detection and sizing. During typical TOFD inspections, A-scans are collected and used to create a gray scale B-scan (side view) image of the weld inspection as *shown in Figure 4*.
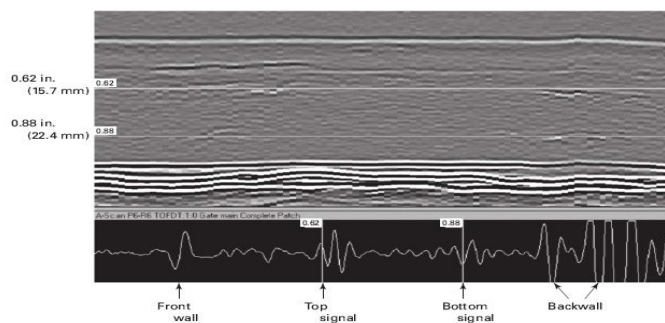

Figure 4: A gray scale B-scan (side view) image [9]

2.3 Flaw sizing techniques.
2.3.1 Flaws can be classified as follows [9]

- On top surface flaws.
- Embedded or under surface flaws.
- On bottom or reflected surface flaws.

2.3.2 Flaw sizing by dB drop technique – PAUT [9,11]

The dB drop technique determines the flaw sizing by comparing the amplitude drop with the maximum obtained amplitude from a mid of flaw. The dB drop technique is an echo dynamic technique, wherein an

ultrasonic probe is moved across the flaws and the amplitude profile is related to the flaw size. This technique is highly dependent on the beam width and the level of reflected signal amplitude, if not corrected for longer metal paths, will result in over-sizing of small defects. PAUT improves the dB drop sizing technique by reducing the beam spreading and enabling sharper focusing.

$$S = 20\,log(\frac{V1}{V2}) = \ 20\,log(\frac{A1}{A2})\,[dB] \tag{2}$$

Written as: S: The difference in sound intensity expressed in decibels (dB), V1, V2, A1 and A2: Two different voltage or sound amplitude measurements**.**

2.3.3 Flaw sizing by tip back diffraction technique – PAUT [9,11-14,26-27].
Tip back diffraction technique of PAUT determines flaw size by measuring the time of flight of the shear diffracted wave from the upper and lower tips as *in Figure 5* or a tip and reflection wave (corner trapped signal) from the defect.

$$H_{crack} = \ \frac{\Delta UT_{corner-tip\ or\ tip-tip}}{cos\,\beta} \tag{3}$$
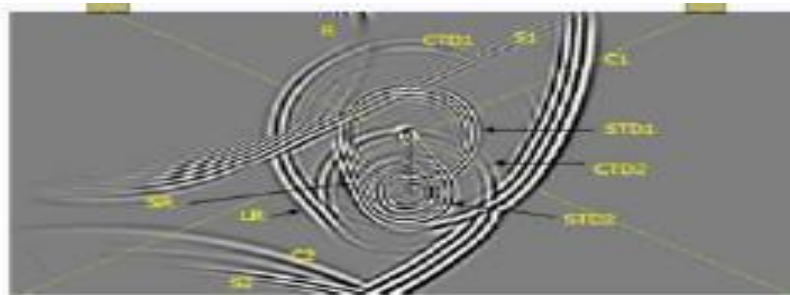
Figure 5: Simulation of diffracted waves generated by both tips of planar defect [26]

(a) Parameters influence on precision of height sizing by PAUT [13-14].
The sensitivity of a PAUT - measurement will be influenced by on suitable specimens and thicknesses, phase array probe frequency, probe aperture, damping and bandwidths as well as material quality.

(1) Suitable specimens and thicknesses
In service inspection are different as most are not cover by Code and are often application – specific with their own specifications. Since the operation has a limited area. The calibration block degrades into a reference block suited for a specific application.
In service inspection requirement let to the development of complex reference block or method, most of methods employ a custom reference blocks with general features listed as below,

- Same or similar micro structure or geometry (for velocity and attenuation) as the inspected component.
- Same or similar surface preparation as the inspected component.
- Large enough to avoid the interference from edge or adjacent reflectors
- Not too heavy

It is recommended that the generic condition to be fulfilled when a suitable reference blocks and thickness is designed.

- Specimen flatness; $< 0.5°$
- Specimen thickness; $> 5\boldsymbol{\lambda}$
- Specimen thickness variation; $0.15\ t_{component}$
- Velocity tolerance; $\Delta v < 0.8\%$ *of component value*
- Attenuation tolerance; $\Delta\propto <10\%$ of linear attenuation coefficient of the component

(2) Phase array probe frequency

In the selection of PAUT probe, there were many frequencies available for selection. The best probe frequency for high sensitivity should be high frequency probe however if it was too high frequency, it could affect the thick wall steel material especially for some small defects at surface due to less depth penetration of wave energy could cause for low detection ability whereas if too low probe frequency, it could cause for less sensitivity and resolution, so the probe frequency should be optimized for a suitable thickness.

(3) Probe aperture

Number of element and probe size also could affect the sensitivity, higher number of element with bigger probe size provide better sensitivity for height sizing because of narrow beam and producing small focal spot. Focal spot size depends on probe active aperture (A or D), wavelength (λ) and focal length (F). Focusing is limited to the near field of the phased array probe.

$$Focal\ spot\ size = \frac{F\lambda}{A}\ or\ 1.02\ \frac{Fc}{fD} \qquad (4)$$

(4) Bandwidth (damping)

Bandwidth (BW) is the frequency range within a given time limits and can be calculated by,

$$BW(Hz) = f_{U-6dB} - f_{L-6dB} \qquad (5)$$

$$BW(\%) = 100\% \cdot \frac{(f_{U-6dB} - f_{L-6dB})}{f_c} \qquad (6)$$

Narrow bandwidth	(15-30%)	best for detection
Medium bandwidth	(31-75%)	detection and sizing
High bandwidth	(76-110%)	best for sizing

Phase array probes typically have a broad bandwidth and piezocomposite material which phase array probes are made of provides high sizing performance.

(5) Material quality

One of the critical feature for height sizing measurement is the metallurgical structure. The ultrasonic velocity is a major factor for time base calibration, attenuation coefficient and sizing. Difference in material quality will affect to height sizing performance by differs in ultrasonically velocity in the material. If input velocity is a higher value than the actual value, the sizing value will have a higher value than the actual value. If the input velocity is lower, the sizing value will decrease. The programmed (or block velocity) must be within ± 80 m/s of the actual test piece material for ±1 mm height.

(b) Sensitivity (Se) of PAUT; the ratio between the output and input voltage for specific set up.

$$Se = 20\ log_{10} \cdot \frac{V_{out}}{V_{in}} \quad [dB] \qquad (7)$$

2.3.4 Flaw sizing by TOFD [9,11-13,22,25-27]

TOFD detect and recode signal diffracted from defect tips for both detection and sizing. The flaw is the signals between lateral wave and back wall echo as showing in *Figure 12 -13*.

(a) Flaw height determination - Flaw height (thru-wall dimension) is determined as follows [9,25]:

(1) Top surface open or connected flaws: The height of a top open flaw is determined by the distance between the top-surface lateral wave and the lower-tip diffracted signal.

(b) Embedded flaws (subsurface): The height of an embedded flaw is determined by (1) the distance between the upper-tip diffracted signal and the lower-tip diffracted signal *as Figure 5* or can be calculated by,

$$D = \left[(\frac{c(td1 + tp)}{2})^2 - s^2\right]^{1/2} \qquad (8)$$

$$Hd \ or \ L = \left[\left(\frac{c(td2 + tp)}{2} \right)^2 - s^2 \right]^{1/2} - D \qquad (9)$$

(2) Bottom or reflected surface open flaws: The height of a bottom-surface connected flaw is determined by the distance between the upper tip diffracted signal and the back wall signal.
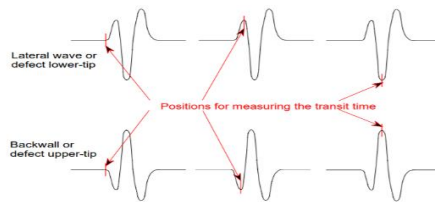
(b) Dead zones [25]
The depth of dead zone in the lateral wave at surface.

$$Dds = \left[\frac{c^2 tp^2}{4} + Sctp \right]^{\frac{1}{2}} \qquad (10)$$

The depth of dead zone in the back-wall signal at reflected surface.

$$Ddw = \left[\frac{c^2(tw + tp)^2}{4} - S^2 \right]^{\frac{1}{2}} - W \qquad (11)$$

Both dead zones can be reduced by decreasing the probe separation or by using probes with shorter pulse length.

Figure 6: Reference position for height sizing by TOFD [28]

(c) Parameters influence on precision of height sizing by TOFD [25].
The precision of a TOFD - measurement will be influenced by timing error, error in sound velocity, probe separation error and error in assumed lateral position of an indication. Under normal circumstance the overall precision or sensitivity will be dominated by the latter,

(1) Errors in the lateral position
The lateral position of an indication is normally assumed to be mid-way between the two probes. The error in depth (δd) due to the error in lateral position (δy) can be calculated by:

$$\delta d = \frac{(c^2 t^2 - 4S^2)^{\frac{1}{2}} \left(\frac{\delta y^2}{c^2 t^2} \right)}{\left[(0.25 - \frac{\delta y^2}{c^2 t^2})^{1/2} \right]} \qquad (12)$$

(2) The limit of precision in the depth of an indication, due to timing errors (δt), can be estimated from:

$$\delta d = \frac{c \delta t (d^2 - S^2)^{\frac{1}{2}}}{2d} \qquad (13)$$

The timing error can be reduced by using a shorter pulse and/or a higher frequency.

(3) The limit of precision in the estimate of the depth of an indication, due to errors in the sound velocity, is given by:

$$\delta d = \frac{\delta c \left(d^2 + S^2 - S(d^2 + S^2)^{1/2} \right)}{cd} \qquad (14)$$

This error is reduced if the probe separation is reduced. Independent calibration of the velocity by measurement of the delay of the back wall echo, with a known wall thickness, greatly reduces this error.

(4) Errors in the distance between the index points (δs) will result in errors in depth-measurement. The error in depth δd can be calculated by:

$$\delta d = \frac{\delta S(d^2 + S^2 - S)}{d} \qquad (15)$$

It should be noted that errors in probe separation can arise from both measurement errors in the distance between the probes, as well as errors in the index point calibration.

(d) The spatial resolution (R) is a function of depth and can be calculated by:

$$R = (c^2(t_d + t_p)^2/4 - S^2)^{1/2} - d \qquad (16)$$

tp is the length of the acoustic pulse and td is the time-of-flight at depth d. The resolution increases with increasing depth and *can* be improved by decreasing the probe separation or the acoustic pulse length.

(e) TOFD probe frequency
UT based on reflected echo which requiring a minimum level of signal amplitude for processing and demonstration. Whereas, TOFD based on diffraction echo therefore even a small signal from the tip of defect can be detected by TOFD. Sound wave penetration is not a major concern in TOFD, thus higher probe frequency is recommended for height sizing by TOFD for the best sensitivity.

3. Experimental Procedure

3.1 Equipment and test plate
3.1.1 Ultrasonic instrument: Omiscan-MX2 (*Omiscan 32:128*); UT machine for both PAUT and TOFD experiments was the same UT brand name and model machine as shown in *Figure 8*. The UT machine brand name was Olympus and the Model was Omiscan - MX2.

3.1.2 Probe (Olympus)
PAUT: 5L64-A2, 5 MHz, 64 Elements, Pitch 0.6 mm, Wedge 33°.
TOFD: IM-10-3, 10 MHz, Single Element, Element size 3 mm, Wedge 70°.

3.1.3. Test Plate.
Prepare 2 test plates, material: A537 Class 1 with 240 x 300 x 28.6t mm and use Electrical Discharge Machining (EDM) creating vertical planar flaws on surface (located at fusion line) and at subsurface (located approximately at mid thickness region). Test plates contained EDM notches oriented to simulate flaws parallel to the weld centerline and major groove faces as guided by ASME Section V Article 4, MANDATORY APPENDIX IX. Flaw sizes were calculated as per specimen thickness and covered three sizes including smaller acceptable size, at rejected size and over the rejected size as *in Table 1*. Welding process was SMAW with double V groove weld. Surface roughness was as rolled condition. Surface was 0.5° incline max.
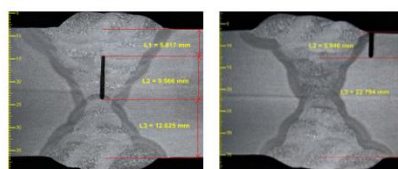
Figure 7: A macro etched specimens for actual defect height measurement.
Table 1: Size and Location of designed vertical planar flaws.

Flaw	Location	Size of vertical planar flaws (mm)				
Parallel	On surface	10(A)	6(B)	4(C)	2.5(D)	1.5(E)
Parallel	Under surface	1.5(G)	2.5(H)	4(I)	6(J)	10(K)

3.2 Experiment set up

Experimental setup divided into three parts which called model. Machine set up and calibration were very essential and a principle part for this experiment as it was used to set up the essential parameters for flaw detection and height sizing. A calibration block (IIW block) and specific reference blocks, made of material ultrasonically equivalent of test plates to be inspected by PAUT and TOFD. Sensitivity was setup creating a Time Corrected Gain (TCG) using side drill holes at different depths as per ASME Section V Article 4. After all testing had been completed, test plates were cut and acid etched across the defect location for height measurement *as illustrated in Figure 7.*

Model 1. Detect and measure planar defects height in test plates using PAUT by tip back diffraction technique. Three sizes of planar flaws including smaller acceptable size, at rejected size and over the rejected size were inspected and height sized by PAUT. Testing and data recording were repeated by 5 times on each plate *as exhibited in Figure 8.* The data was corrected and calculated to determine mean, mean error and standard deviation of flaw height sizing.

Figure 8: Detection and measuring planar defects height in test plates using PAUT.

Model 2. Detect and measure planar defects in test plates using TOFD. Three sizes of planar flaws including smaller acceptable size, at rejected size and over the rejected size were inspected and height sized by TOFD. Testing and data recording were repeated by 5 times on each plate *as exhibited in Figure 9.* The data was corrected and calculated to determine mean, mean error and standard deviation of flaw height sizing

Figure 9: Detection and measuring planar defects in test plates using TOFD**.**

Model 3. Compare and analyze experimental results from Model 1 and 2 to determine which UT technique was more suitable in detection and height sizing ability of planar defects for on and under surfaces.

Table 2: PAUT Parameters:

Probe	Freq.	Element	Aperture / Elevation	Pitch	Sweep angle	Velocity	Thk.
5L64-A2	5 MHz	32/64	38.4/7 mm	0.6 mm	30 -70	3215	28.6 mm

Table 3: TOFD Parameters:

| Probe	Freq.	Element	Element size	Refracted angle	PCS	Diffracted wave Velocity	Matl's thk.
IM-10-3	10 MHz	Single	3 mm	70	104 mm	5890	28.6 mm

4. Results & Discussion

Model 1.
4.1 Flaw detection and height sizing by phased array ultrasonic test (PAUT)
(a) Planar defects under surface.

PAUT display showed echoes diffracted from the upper tip and lower tip of the flaw. No refracted amplitude signal from the mid. of flaws was visible on the S-scan screen as *in Figure 10(a).* In a case that upper tip signal was more clearly seen than the lower tip, it could result in erroneous interpretation. Thus, a skilled and experienced PAUT interpreter was required. The highest amplitude was assumed to be the tip end of planar defect.
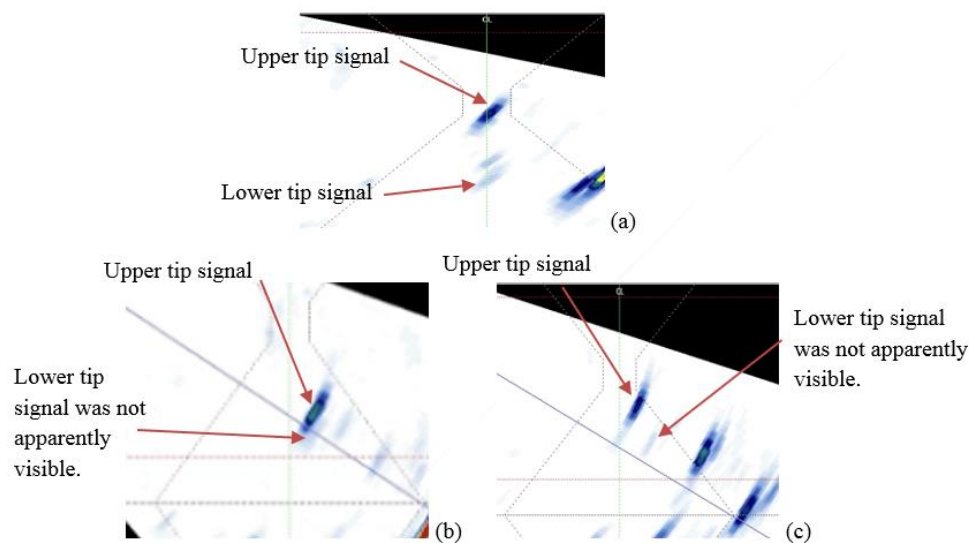
Figure 10: Signal of planar defects high as (b) 1.98 mm and (c) 4.56 mm; the lower tip was not apparently visible on the S-scan screen as it should be. Thus, this would be a weak point of PAUT for planar defects approximately high as below 5 mm. Height sizing could be done through careful practices.

(b) Planar defects on surfaces.

The PAUT display showed wave echo diffracted back from the embedded tip and reflected echo from the corner of the flaw as in *Figure 12*. No reflected amplitude wave signal from the mid of flaws was visible. In the case that the corner echo was larger and more clearly seen (saturated signal) than the tip, it could cause incorrect interpretation. For a very small planar defect, tip signals merged with each other as in *Figure 11*.
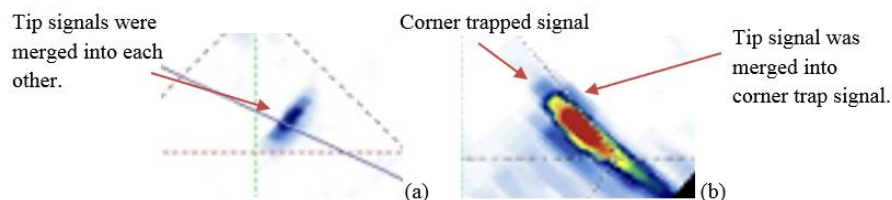

Figure 11: For a very small planar defect, tip signals merged with (a) each other or (b) tip signal merged into corner trap signal, amplitude drop technique was a method for height sizing: actual height was 1.37 mm. Height sizing by 3dB drop was 3.64 mm and by 6dB drop was 4.45 mm [overestimated by 165% and 224% respectively].
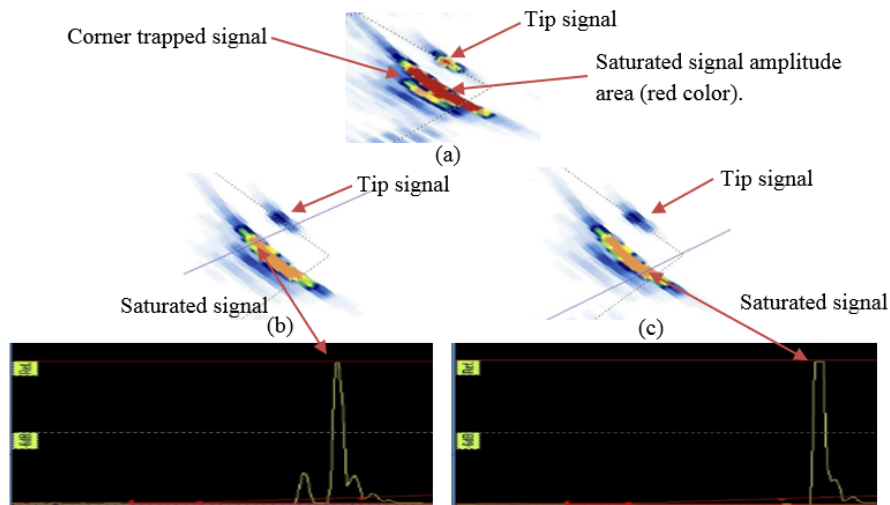
Figure 12: Gain reducing could be used to find the peak amplitude, but it might not be useful if receiving A(%) > 200% because the saturated amplitude (broad red area) was inadequacy reduced. (a) Showing a tip and reflected signal from a planar defect in the material before gain reducing. (b) Showing a tip and reflected signal from a planar defect in the material after gain reducing (reducing to a lowest dB as possible).
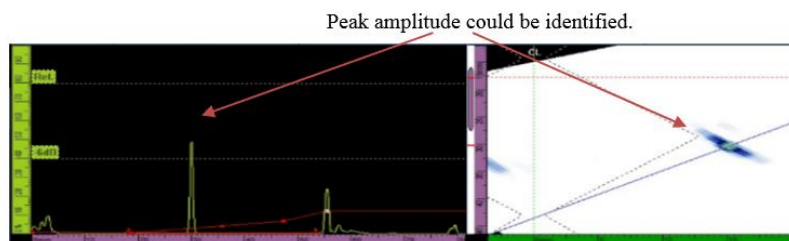
Figure 13: Gain reducing might be useful for height sizing if receiving A (%) < 200% [Peak amplitude could be identified because the saturated amplitude was adequacy reduced].
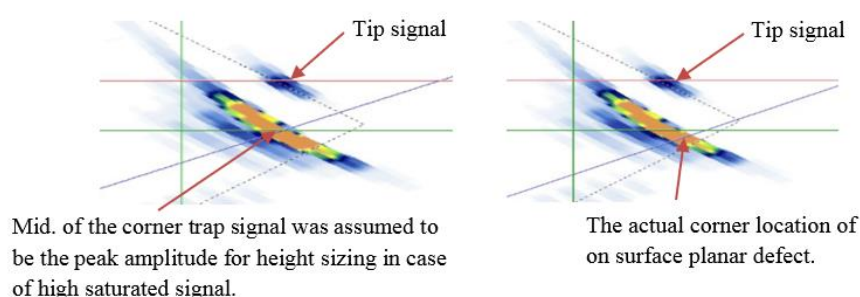
Figure 14: PAUT height sizing: the middle of the saturated area potential not being the exact defect corner position; actual hight was 5.9 mm, PAUT height reading showed 5.58 mm (undersizing).

Model 2.
4.2 Flaw detection and height sizing by time of flight diffraction technique (TOFD)

The diffracted signals from flaw tips were displayed between the lateral and back-wall reflected waves as *in Figure 15*. Defects on the top and bottom surfaces were difficult to detect due to the dead zone in the lateral wave and because of the dead zone in the back wall signal. Flaw location and height sizing could have some errors due to TOF locus [13], since the time of diffracted waves depended on the flaw position relative to probes. The best flaw position for accurate height sizing was the middle between probes. Coupling, surface roughness and alignment could also cause some errors on height sizing as *in Figure* 16. Speed of scanning must be carefully controlled for data recieval and the digitization process. In spite of these limitations, TOFD was fould to be an accurate UT technique for defect height sizing as in *Tables 4,5 and 6 and Figures 21-22*. Since the conditions and parameters must be properly selected and controlled, stand-alone fast scanning by TOFD method was not recommended. This UT technique should be used as a method for reconfirmation or used in combination with PAUT. TOFD should also be used as a suitable method for crack growth monitoring.
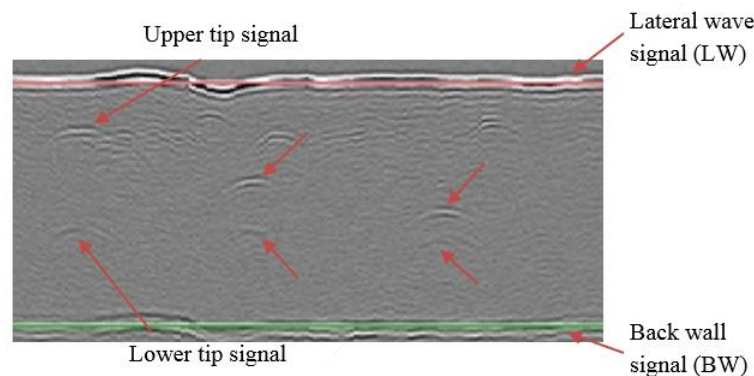

Figure 15: Signals and height sizing by TOFD.
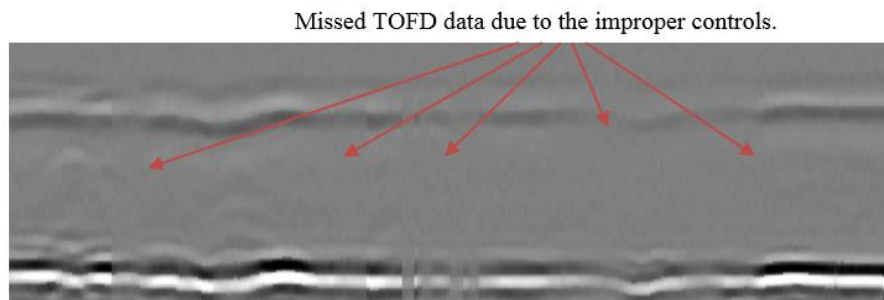
Figure 16: Missed TOFD data and error due to coupling, surface roughness and alignment during scanning.

4.3 Limitation of PAUT and TOFD on small planar defects.

On surface small planar defect "G" (high as 1.37 mm) could be detected by TOFD but was not able to be sized due to being masked by dead zones as *in Figure 17 (c)*. For tip back diffraction technique, small planar defect "G" (high as 1.37 mm) could be detected and also was not able to be sized due to tip signals being merged with each other as in *Figure 17 (a)*. The only method for height sizing for this defect was dB drop technique. However, sizing by dB drop technique on a very small planar defect on surface resulted in some error (oversizing about 200% by 6 dB drop) due to strong signal amplitude from the corner leading to missed interpretation.

On surface planar defect "H" (high as 2.8 mm) was not able to be sized by TOFD, whereas PAUT by tip back diffraction was able to size with good accuracy as in *Figure 17 (b)(c) and Table 5-6*, thus PAUT by back diffraction technique could size smaller on surface planar defect. However, in the case of under surface planar defects, TOFD could size smaller planar defects. The height sizing accuracy using TOFD for under surface was also high as in *Table 4*.
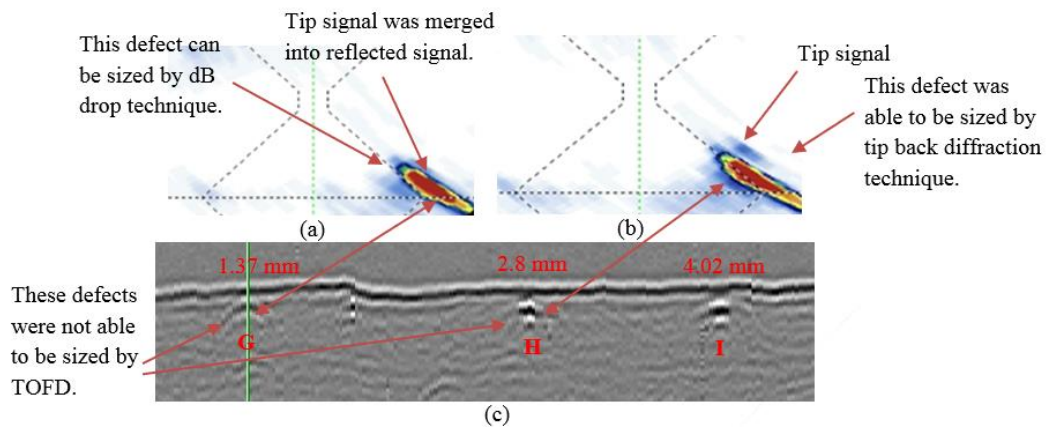
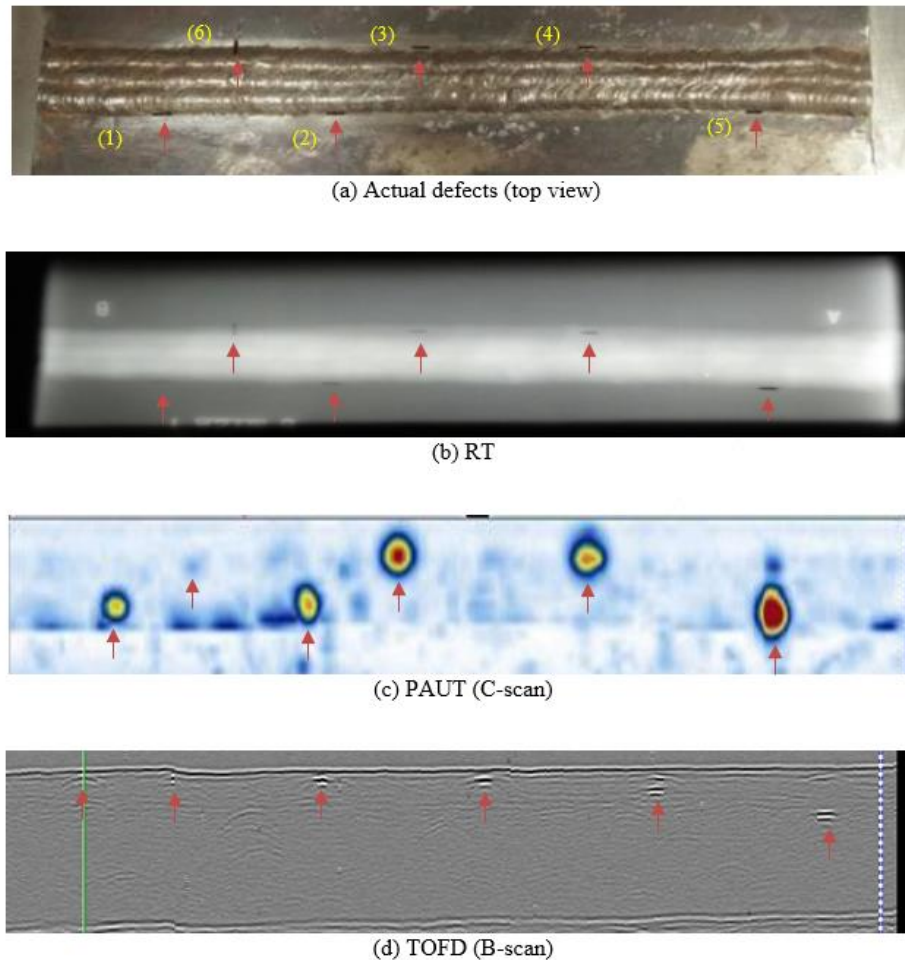**Figure 17:** Small top surface defects on the screen by TOFD compared with PAUT.
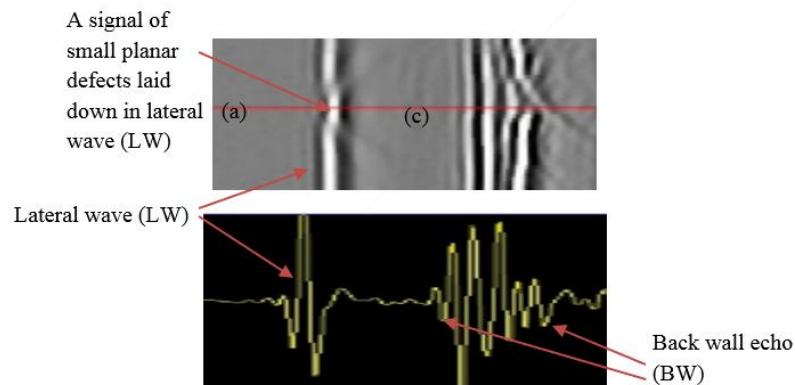
Figure 18: TOFD signal of a small defect on the top suface. [Detection was possible but height sizing was difficult or impossible due to the defect being masked by the dead zone (LW)].
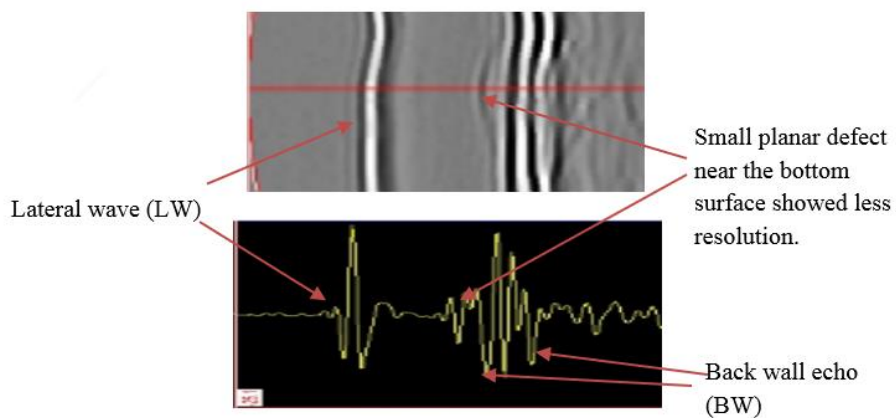
Figure 19: TOFD signal of small defect on the bottom suface. [Detection was possible but height sizing was difficult to interpret].

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Model 3.
4.4 Comparison of detection and height sizing ability for planar defects.

(a) Actual defects (top view)

(b) RT

(c) PAUT (C-scan)

(d) TOFD (B-scan)

Figure 20: TOFD and PAUT could detect all defects, thus TOFD was not blinded for small defects high below 5 mm. however height sizing by TOFD was limited for some small defects. [defects high as (1) 1.37 mm, (2) 2.8 mm, (3) 4.02 mm, (4) 5.9 mm, (5) 9.67 mm repectivly and (6) 4 mm (trasverse flaw)].

Table 4: Under surface defects [Standard Deviation: tip back diffraction ±0.2 mm and TOFD ±0.12 mm].

No.	Designed flaw height (mm)	Actual flaw height[2] (mm)	Mean height [5 repeated scans] (mm)		Mean error (%)		Different [Individual max. or min. height – actual height] (mm)	
			PAUT[1]	TOFD	PAUT	TOFD	PAUT	TOFD
1	1.5	1.37[3]	detected	1.38	-	1%	-	-0.11
2	2.5	1.5	1.75	1.53	17%	2%	0.47	0.11
3	4	1.98	2.01	1.91	2%	-4%	0.20	-0.13
4	6	4.56	4.23	4.71	-7%	3%	-0.35	0.38
5	10	9.56	9.27	9.42	-3%	-1.5%	-0.43	-0.30

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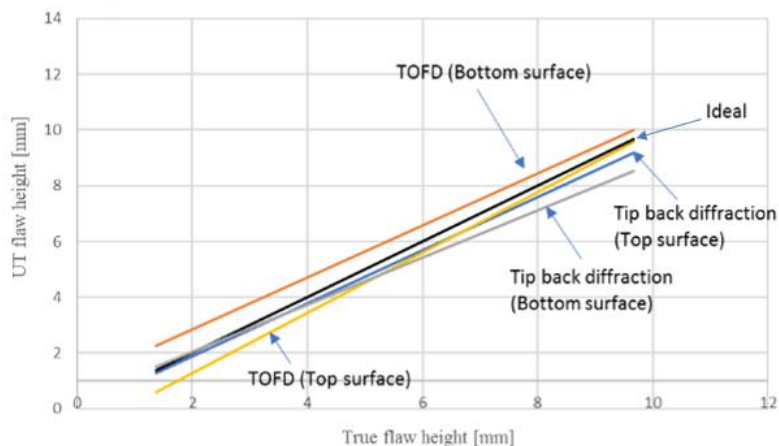**Table 5**: On top surface defects [Standard Deviation: tip back diffraction ±0.2 mm and TOFD ±0.5 mm].

No.	Designed flaw height (mm)	Actual flaw height[2] (mm)	Mean height [5 repeated scans] (mm)		Mean error (%)		Different [Individual max. or min. height – actual height] (mm)	
			PAUT[1]	TOFD	PAUT	TOFD	PAUT	TOFD
1	1.5	1.37[3]	detected	detected	-	-	-	-
2	2.5	2.8	2.95	detected	5%	-	0.27	-
3	4	4.02	3.78	3.77	-6%	-6%	-0.39	-0.36
4	6	5.9	5.04	5.07	-15%	-14%	-1.05	-1.38
5	10	9.67	9.44	9.73	-2.5%	1%	-0.48	0.65

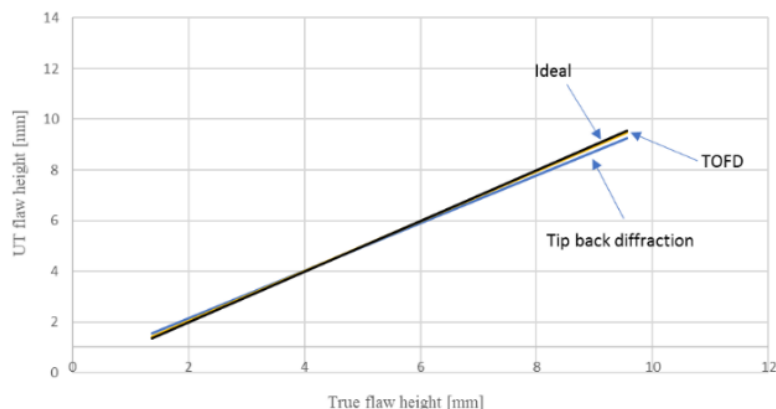**Table 6:** On bottom surface defects [Standard Deviation: tip back diffraction ±0.17 mm and TOFD ±0.5 mm].

No.	Designed flaw height (mm)	Actual flaw height[2] (mm)	Mean height [5 repeated scans] (mm)		Mean error (%)		Different [Individual max. or min. height – actual height] (mm)	
			PAUT[1]	TOFD	PAUT	TOFD	PAUT	TOFD
1	1.5	1.37[3]	detected	detected	-	-	-	-
2	2.5	2.8	2.85	detected	2%	-	0.31	-
3	4	4.02	3.81	4.45	-5%	11%	-0.37	0.78
4	6	5.9	4.96	6.36	-16%	8%	-1.02	0.70
5	10	9.67	8.67	10.06	-10%	4%	-0.95	1.06

Noted: (1) Tip back diffraction technique of PAUT

(2) Direct measurement from macro etched specimen.

(3) It was able to be sized by dB drop but seems likes oversizing.

"Detected" means defects could detected but height sizing could not be performed.

Figure 21: Correlation between PAUT and TOFD height data and true measurement (On surfaces).

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Figure 22: Correlation between PAUT and TOFD height data and true measurement (Under surface).

4.4.1 On surface defects [On top and bottom surfaces]

(a) Signals of planar defect high as below 5 mm were not blinded in TOFD. For the detection by TOFD for small defects near sufaces, detection was possible but height sizing was difficult or impossible due to dead zone or poor resolution as in *Figures 18-20 and Tables 5-6*.
(b) Both TOFD and tip back diffraction techniques had similar height sizing accuracies for on surface planar defects as in *Figure 21 and Tables 5-6*.
(c) *TOFD* was not able to measure the defect height of 2.8 mm and smaller due to the dead zone of the lateral wave (LW) or backwall echo (BW), whereas tip back difffraction was able to measure this defect with good accuracy, thus PAUT could size smaller defects as in *Figure 17 and Tables 5-6*.
(d) Neither TOFD and tip back diffraction were able to measure a very small defect as high as 1.37 mm high due to the dead zones from interference waves or tip signals merged into corner reflrected signal as in *Figure 17(a)*, whereas dB drop technique was able to measure however dB drop technique resulted in error (oversizing about 200% by 6 dB drop) due to very strong signal amplitude from the defect corner leading to missed interpretation.
(e) Tip back diffraction technique tended to provide the undersize tendency, the tendency increased with defect height, especially at surfaces because of the broad saturated signal area and mid. of the saturated area potentially not being the exact defect corner position for height sizing as in *Figures 12,14 and 21*.

4.4.2 Under surface defects [approximately at mid thickness region]

(a) Signals of planar defect high as below 5 mm were not blinded in TOFD and height sizing showed good accuracy as in *Figure 20 and Table 4*. Whereas, it had some very concerns on PAUT because the tip was not apparently visible as it should be. This would be a weak point of PAUT for mid-wall planar defects approximately high as below 5 mm.
(b) TOFD showed more accurate height sizing than the tip back diffraction technique for *Under surface planar defects* as in *Figure 22 and Table 4*.
(c) Tip back diffraction was not able to measure defect height of 1.37 mm due to tip signals being merged with each other as in *as in Table 4 and Figure 17(a)*, whereas TOFD was able to detect both tips and measure height with good accuracy, thus TOFD could size smaller *Under surface planar defects.*
(d) Tip back diffraction tended to provide undersizing tendency, the tendency increases with defect height as *in Figure 22*.
(e) Since PAUT tended to provide undersizing for both on surfaces and under surface defects and showed less accuracy than TOFD, thus PAUT should not be used as a stand-alone scanning technique in the case of requiring very high reliability on height sizing such as Fitness-for-service calculation or Engineering Critical Assessment (ECA) analysis and a combined method by PAUT and TOFD was recommended.

5. Conclusions

5.1 TOFD is better technique than PAUT for height sizing of *Small under surface planar defects.* TOFD also can size smaller defect.

5.2 *Planar defects which of size below than 5 mm* are not blind and could be detected in both TOFD and PAUT techniques. For *Under surface defects,* TOFD exhibits good detection and accurate height sizing whereas it shows some very concerns on detection in the case of PAUT because the tip is not apparently visible as it should be. Therefore, it could be easily misinterpreted on the height sizing.

5.3 TOFD and tip back diffraction techniques show similar height sizing accuracies *for on surface planar defects.*

5.4 Tip back diffraction technique could size *smaller on surface planar defect*s with good accuracy, so PAUT is better than TOFD for height sizing of *small on surface planar defects*.

5.5 Tip back diffraction technique tends to provide the undersizing tendency, especially defects on surfaces because of the broad saturated signal area and the middle of the saturated area potential not being the exact defect corner position causing height sizing is difficult to interpret. The undersizing tendency increases with defect height.

5.6 PAUT *shall not be used as a stand-alone scanning technique* in the case of requiring *high reliability on height sizing* such as Fitness-for-service calculation or Engineering Critical Assessment (ECA) analysis. A combined method by PAUT and TOFD is recommended.

5.7 TOFD *shall be not suitable as a stand-alone fast scanning technique* or *in replacing the PAUT method*. TOFD should be used as a confirmation method for *known cracks or crack growth monitoring*.

5.8 Planar defect height sizing by ultrasonics (UT) requires special skills and suitable equipment performance with experienced personnel. Therefore, procedure, equipment performance and personnel skills must be demonstrated before starting a job.

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