TOFD Examination of HDPE Butt Weld Fusion Joints.

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Abstract

Present paper shows some relevant aspects to be considered when TOFD is required for HDPE Butt Fusion Welded Joints examination. The influence of some relevant parameters as PCS, noise, frequency content, amplitude relationships of pulses and the use of water path wedges are addressed. Brief comparison between steel and HDPE approaches are presented.

1. Introduction

HDPE is a thermoplastic polymer, in other words, the material recover his properties after cooling and can be subjected to considerable heating and cooling cycles without loose applicability. HDPE is one of three major branches of Polyethylene (the other two are low and medium density PE) (1).

Price, high corrosion resistance, easy manipulation, transportation and handling (HDPE is a very light product), faster and easy welding process, flexibility and other characteristics have made HDPE pipes popular in industrial and domestic facilities.

Applications like discharge of wastewater doesn't require inspection even hydrostatic test. But other industrial uses like transportation of water for mining processes, low and medium pressure gas lines, emergency fire systems and Class 3 nuclear piping systems, could require a considerable extension of inspection. Classical Nondestructive Testing Methods as Radiography and Ultrasonic Shear Waves angle beam doesn't shows good results. The properties of this product makes difficult to work with shear waves since attenuation of this waves is an issue in this type of materials.

In Article 4 of 2015 ASME BPVC Section V edition, the Ultrasonic Examination of fusion joints of HDPE pipes has been included in the mandatory Appendix X.

Volumetric evaluation of HDPE fusion butt joints can be performed with excellent results using TOFD technique. Water path wedges has been introduced a few years ago by Olympus® with markedly improvements increasing SNR, reducing attenuation and the dispersive effect of Rexolite® over the frequency content of the ultrasonic pulse. This combined effects allow production of high quality D-Scan images.

2. Probe Center Separation (PCS)

Most codes ask for a minimum of variables to be considered during the TOFD procedure development. ASME BPVC 2015 Section V Article 4, ask for the classical parameters of table T-421 and others showed at Table III-422 and Table X-421 related with specific aspect of inspection as instrument manufacturer and model, software employed, sizing method, scanning area, etc.

One of the critical points related with inspection procedure, is the proper selection of the Probe Center Separation (PCS). The geometry of TOFD inspection, produces the following expression for the PCS as a function of refracted axis intersection (as shown in **Figure 1**):

$$PCS = 2dTan(\emptyset) \qquad \text{(Ec. 1)}$$

Where d is the depth of the "intersection" point, and $\emptyset$ is the refracted angle.

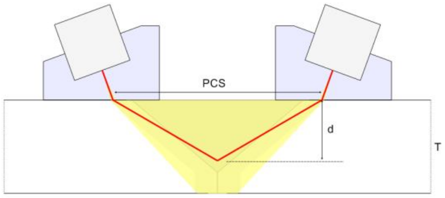


Figure 1. Classical TOFD arrangement.

As the part thickness increases, additional setups must be included in order to properly isonify the material volume. ASME BPVC 2015 Section V Article 4 Appendix O, presents recommended number of setups as well as the "d" values as a function of material thickness.

It is important to consider that codes recommendation for volume coverage were developed using steel as a material to be inspected. A classical approach for steel, for thickness (T) less than 50 mm, recommend $d = \frac{2}{3}T$, where T is the part thickness. For HDPE and thickness less than 50 mm, We have experimentally seen that $d = \frac{4}{5}T$ as the intersection ultrasonic axis depth could result in better image definition, including discontinuities near the pipe surface. The situation is represented in **Figure 2**. During HDPE joint inspection, It seems a good recommendation to do some tests to best choice of d to set the optimum PCS.

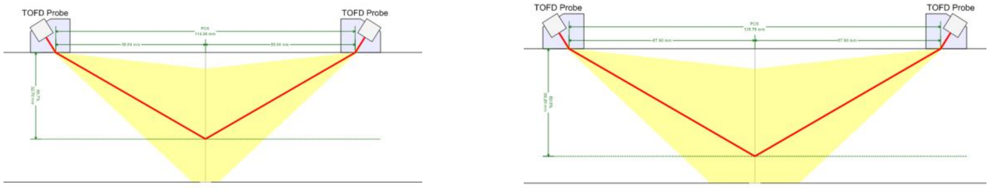


Figure 2. TOFD PCS for $d = \frac{2}{3}T$ (left) and $d = \frac{4}{5}T$

3. Water Path Wedges

Water path wedge is made as a conventional wedge but with a cylindrical hole water filled (or other fluid) trough convenient channels during scanning. Water wedges are an excellent choice since attenuation of water (2) is considerable inferior than attenuation in other conventional plastic materials used for wedges (including Rexolite ®). The use of water wedges increase the SNR, reducing attenuation and frequency dispersion associated with common wedge materials as can be seen in **Table 1**.

Water path wedges with Teflon surface contact adaptor shows excellent performance over HDPE product surface. **Figure 3** presents a water path wedge made by Olympus®.

Table 1. Attenuation in some related materials or mediums.

Medium	Attenuation [dB/mm]	At a frequency
Water (3)	0.00087	2 MHz
Rexolite (7)	0.32	2.25 MHz
HDPE (2)	0.3	2.25 MHz

Figure 3. Water path wedges manufactured by Olympus® (4)

Water path wedges also reduce the problem of energy loss due to poor contact surface matching area. The Teflon contact ring avoids fast water leak, reducing the quantity of water required during the test. The water channel serves as a guide wave and assure that almost all UT beam make contact with the pipe surface. Shear waves can´t propagate in water medium reducing possible noisse and undesirable waves inside wedge material.

The use of constant supplied water for inspection introduce positive effects related with material temperature stabilization for inspection. Temperature changes produce velocity propagation variations with associated sizing errors (5). Change of lateral wave position during one scan, due to velocity changes, is common during field inspection of HDPE pipes when scanner crosses areas at different temperatures induced by different Sun exposure.

This type of wedges can have a drawback respect to high temperature applications or material corrosion related aspects not common found in HDPE pipes.

4. Noise and Phase Observation.

A typical HDPE TOFD A-Scan is presented in **Figure 4**, the A-Scan was acquired using a PCS=113 mm, 6 mm diameter 2.25 MHz transducer and 60 degrees refracted longitudinal wave in 49 mm thickness HDPE with water path wedges. The Scan Plan can be seen in **Figure 5**. The equipment used was an Olympus® OMNISCAN MX2™.

One of the requirements of ASME BPVC Sec. V, Art. 4, App III (2015) is that the noise amplitude should not be superior to 10% FSH, an accepted noise range is 5-10 FSH. **Figure 6** clear shows that amplitude noise is below 8% FSH, in the worst case is SNR>9:1 (or 19 dB).

The excellent SNR achieved produce a clear TOFD D-Scan image, as can be seen in **Figure 7**.

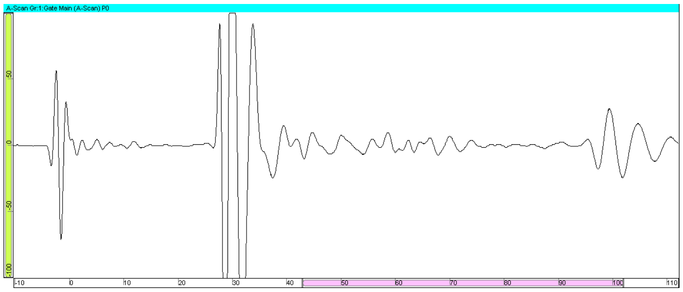


Figure 4. A-Scan for TOFD configuration in 49 mm thick HDPE using a PCS=113 mm, 6 mm 2.25 MHz diameter transducer.

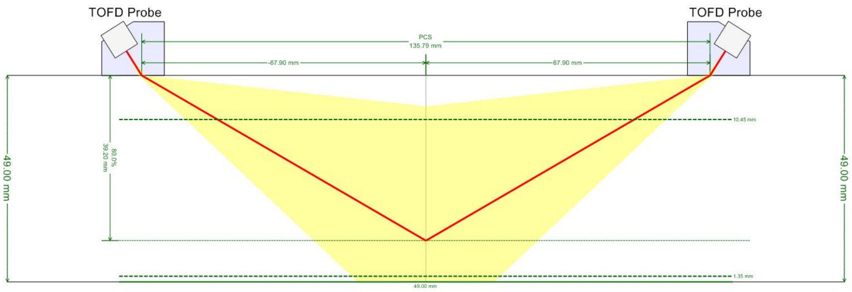


Figure 5. TOFD transducer position and beam intersection depth used for the A-Scan acquisition of **Figure 4**.

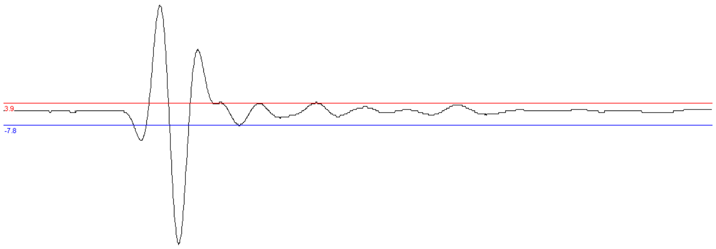


Figure 6. Noise amplitude in the A-Scan. Lateral Wave followed by "noise" oscillations.

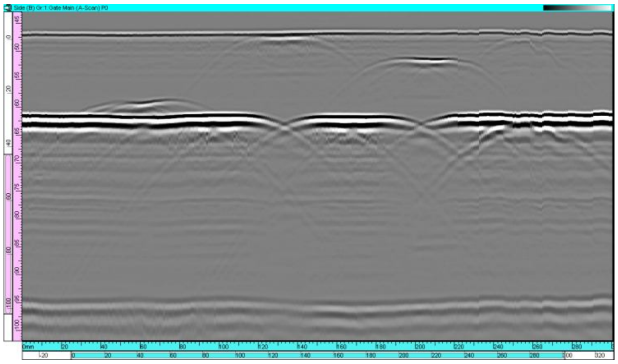
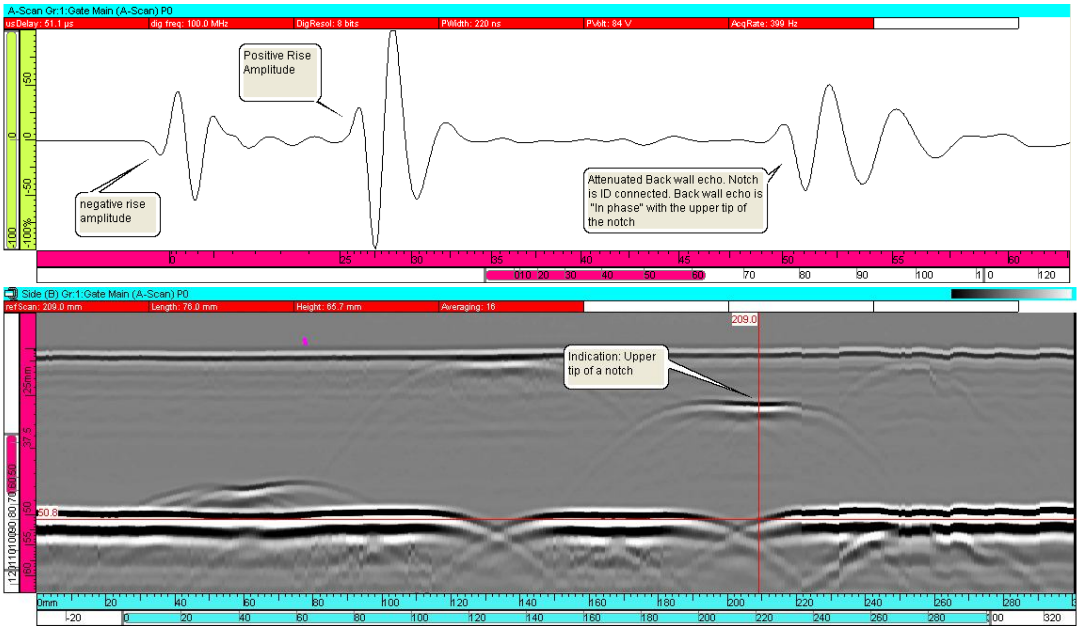


Figure 7. TOFD image taken on HDPE 49 mm thickness sample including 5%, 75% and 50% depth and 25 mm length notches and 75% thickness flat bottom hole (ordered from left to right).

High SNR, help to analyze the phase relationships in the image signals which help to discriminate the tips of the discontinuity (upper or lower tip) for sizing purposes.

Figure 8 presents the B-Scan where a midwall notch is clear visible. The A-Scan including lateral wave and upper tip diffracted signal is presented. It is possible to observe that the approximated rule of phase inversion relationship is satisfied by the two pulses. The lateral wave begins with “negative rise amplitude” while the indication pulse begins with a positive one. Backwall echo (strongly attenuated by ID connected flaw) is in counter phase with lateral wave as predicted by theory.


A-Scan Gr:1:Gate Main (A-Scan) P0
usDelay: 51.1 µs
dig.freq: 100.0 MHz
DigResol: 8 bits
PWidth: 220 ns
PVolt: 84 V
AcqRate: 399 Hz

Positive Rise Amplitude

negative rise amplitude

Attenuated Back wall echo. Notch is ID connected. Back wall echo is "In phase" with the upper tip of the notch

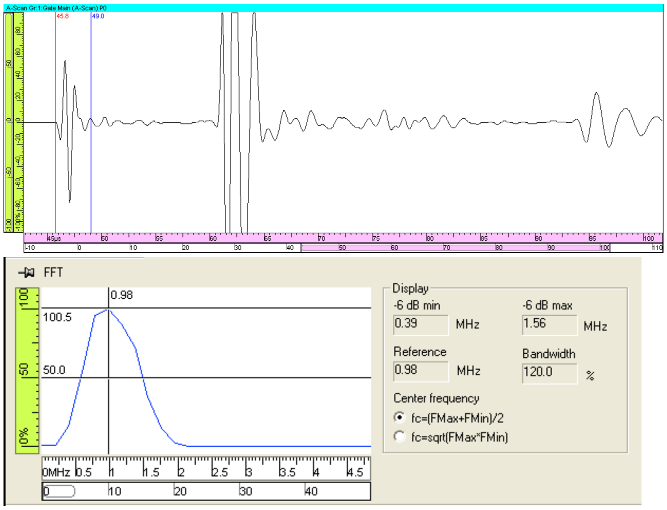
Side (B) Gr:1:Gate Main (A-Scan) P0
refScan: 209.0 mm
Length: 76.0 mm
Height: 65.7 mm
Averaging: 16

Indication: Upper tip of a notch

Figure 8. Phase relationships between lateral wave and the upper tip of an ID connected Notch.

5. Frequency and Amplitude Characteristics

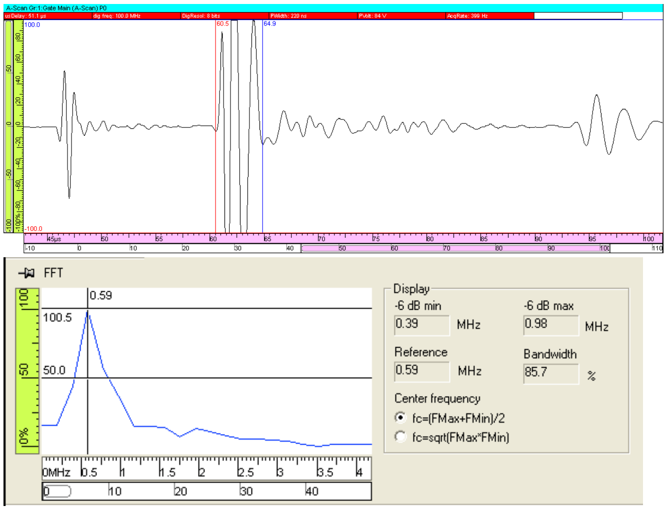
The dispersive nature of HDPE makes the peak frequency of the Lateral Wave considerable inferior to the peak frequency of the transducer but higher of the back wall echo peak frequency. This fact completely differs from steel inspection using Rexolite™ wedges. The lateral wave on steel usually has markedly inferior frequency content compared to the back wall echo. The frequency content of Lateral and Back Wall Echo are presented in **Figures 9** and **Figure 10**, respectively.


A-Scan Gr:1:Gate Main (A-Scan) P0

FFT

Display
-6 dB min 0.39 MHz
-6 dB max 1.56 MHz
Reference 0.98 MHz
Bandwidth 120.0 %
Center frequency
● fc=(FMax+FMin)/2
○ fc=sqrt(FMax*FMin)

Figure 9. Frequency content of Lateral Wave.
Peak Frequency = 0.98 MHz
Bandwidth = 120%
Pulse Width at -20dB = 3.2 µs
Transducer peak frequency= 2.25 MHz.



Display
-6 dB min 0.39 MHz
-6 dB max 0.98 MHz
Reference 0.59 MHz
Bandwidth 85.7 %
Center frequency
● fc=(FMax+FMin)/2
○ fc=sqrt(FMax*FMin)

Figure 10. Frequency content of Back Wall Echo.
Peak Frequency = 0.59 MHz
Bandwidth = 85.7%
Pulse Width at -20dB could not be well established since signal is saturated. Transducer peak frequency= 2.25 MHz.

Mode converted echo in HDPE exhibit a very low amplitude, even less than lateral wave, which is a relevant difference from steel situation. Shear wave is strongly attenuated in HDPE this produce a low amplitude mode converted echo in HDPE. In high thickness pipe, the mode converted echo could pass unseen. **Figure 11** shows the mode converted amplitude compared to Lateral Wave and Back Wall Echo.

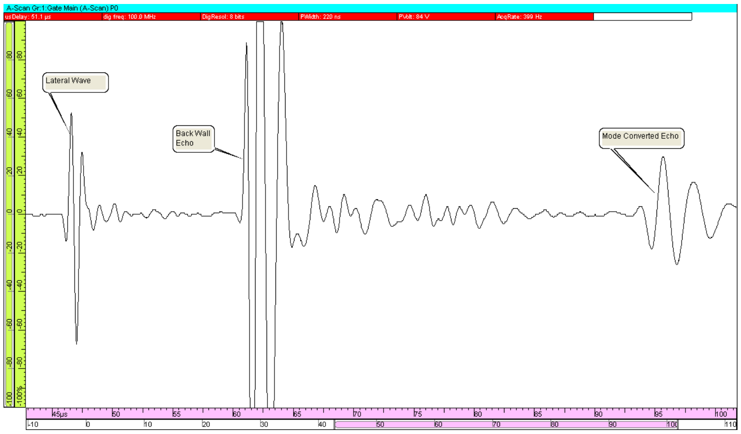


Figure 11. Low amplitude mode converted echo could be seen at the end of the A-Scan.

Since Mode Converted region could not be useful (a difference with steel case), the range could be selected just to include the lateral wave and Back Wall Echo, including 1 to 3 µs before the lateral wave and a the complete waveform of back wall echo. Most part of times weld discontinuities lies in the vertical plane between two transducers and no defects are expected beyond the fusion zone, so in any case mode converted information is not as relevant as in steel.

6. Dead Zones

As in all TOFD conventional applications a considerable surface dead zone could be an issue. HDPE also presents the same drawback. A conservative approach to estimate the surface dead zone (D_s) could be calculated with the following equation (6):

$$D_s = \left[\left(\frac{c^2 t_p^2}{4}\right) + S c t_p\right]^{\frac{1}{2}} \qquad \text{(Ec. 2)}$$

Where:

c : Longitudinal wave velocity
t_p: Lateral wave pulse length at -20 dB
S: Half the distance between the index point of two transducers

Using the values related with the acquisition of B-Scan of **Figure 7**, $c = 2.4\ \frac{mm}{\mu s}$, $S = 56.5\ mm$, $t_p = 1.7 \mu s$, the surface dead zone is:

$$D_s \cong 15\ mm.$$

The back wall dead zone (D_w) can be estimated using the equation (6):

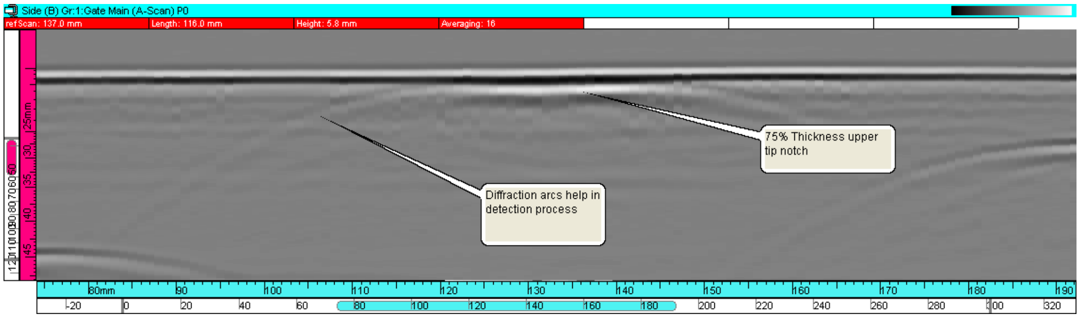
$$D_w = \left[\left(\frac{c^2 (t_p + t_w)^2}{4}\right) - (S^2)\right]^{1/2} - H \qquad \text{(Eq. 3)}$$

Where:
t_w: time of flight of back wall echo
H: Thickness of the piece

Using the previous values and $t_w = 62\ \mu s$, measured in the A-Scan (or by Pythagoras). The back wall dead zone is:

$$D_w = 2.5\ mm$$

Figure 12, shows that upper tip of 75% notch height could be seen in close proximity with the actual upper dead zone (although the notch tip is 3 mm inside theoretical dead zone), diffraction arcs can assist the interpreter to confirm the detection.



Side (B) Gr:1:Gate Main (A-Scan) P0

refScan: 137.0 mm | Length: 116.0 mm | Height: 5.8 mm | Averaging: 16

Figure 12. Upper tip of 37 mm height notch (75% of thickness). The upper tip could be detected despite is beyond the theoretical upper “dead” zone.

Figure 13 show the measurement cursor at 15 mm, the calculated theoretical depth of surface dead zone and the tip of the notch which is close to 12 mm depth (3 mm inside this zone).

Calculations using equations (2) and (3) seems some conservative. A better option could be experimentally size this “dead” zones using notches in a reference block.

The ESBEAMTOOL 5 shows different values from those calculated using the above expressions (2) and (3), as shown in **Figure 5**. The reason could be the theoretical t_p value software uses.

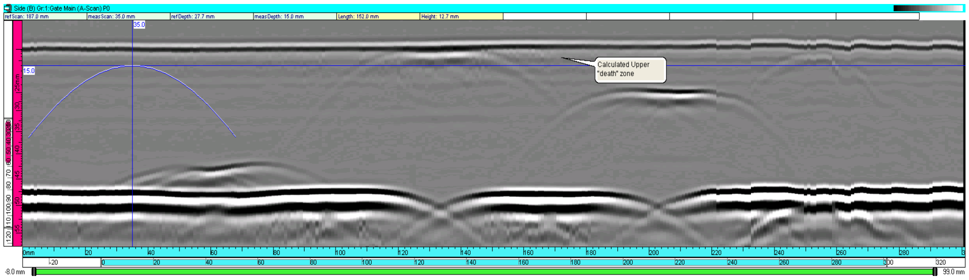


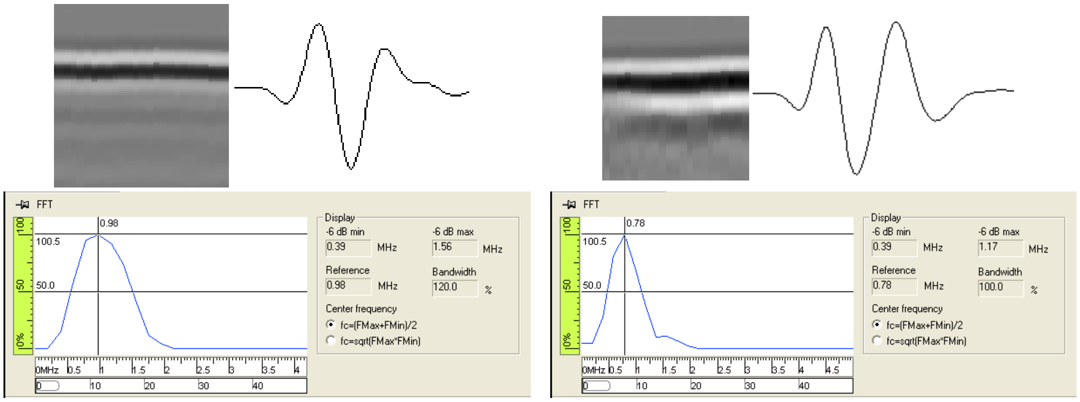
Figure 13. Calculated Surface Dead Zone and a upper tip notch signal inside this zone.

7. Image Analysis

TOFD images of HDPE Fusion Butt Welds with water wedges, usually are acceptable with reasonable low noise and seems doesn't present many difficulties to be analyzed. Strategy for analysis could be:

- Explore the lateral wave amplitude and frequency content

When a variation in coupling exists, the variation of the lateral wave amplitude shall be correlated with variation in back wall echo and mode converted echo amplitude (if mode converted is observed). Suddenly variations, most cases reduction or in apparent augmentation of lateral wave amplitude without variation of other pulses usually is an indication that there exist the possibility that a discontinuity is present associated to the upper region. This situation is presented in **Figure 14**.



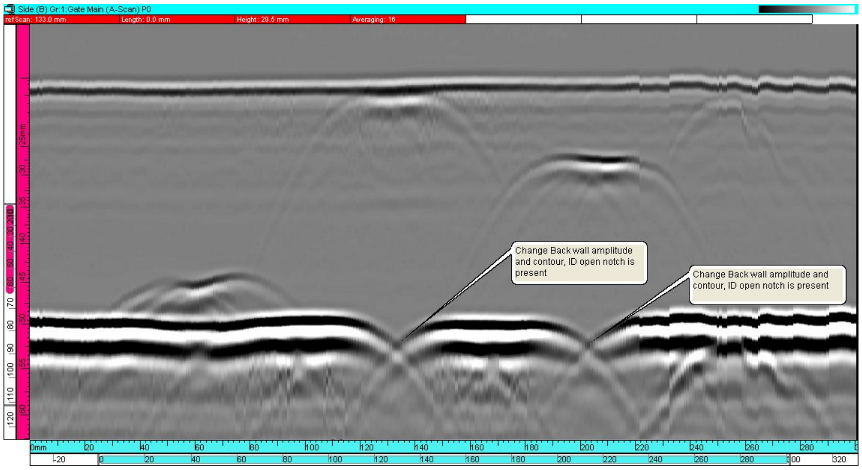
Display
-6 dB min 0.39 MHz
-6 dB max 1.56 MHz
Reference 0.98 MHz
Bandwidth 120.0 %
Center frequency
● fc=(FMax+FMin)/2
○ fc=sqrt(FMax*FMin)

Display
-6 dB min 0.39 MHz
-6 dB max 1.17 MHz
Reference 0.78 MHz
Bandwidth 100.0 %
Center frequency
● fc=(FMax+FMin)/2
○ fc=sqrt(FMax*FMin)

Figure 14. Variation of the lateral wave amplitude, bandwidth and peak frequency. (left) unflawed zone, (right) flawed zone.

- Explore the back wall echo amplitude variation

A reduction of the amplitude of the back wall echo usually means something happen at this region, small reduction even. A reduction of amplitude accompanied with a change of contour also means a discontinuity is present. As can be seen **Figure 15**.



Change Back wall amplitude and contour, ID open notch is present

Change Back wall amplitude and contour, ID open notch is present

Figure 15. Change in the amplitude and contour of back wall echo.

- Explore the coincidence of upper indications and back wall echo amplitude variations

It is very important to see if changes in the back wall eco are synchronized with changes in the upper region of the image, this could be the upper tip of an ID connected discontinuity. If the image is not carefully analyzed the tips of a high height discontinuity could be interpreted as isolated indications, as shows **Figure 16**, a supplementary UT technique as Phased Arrays could clarify the situation.

To increase the POD, Phased Array could be applied with water wedges and longitudinal waves $^{(8)}$.

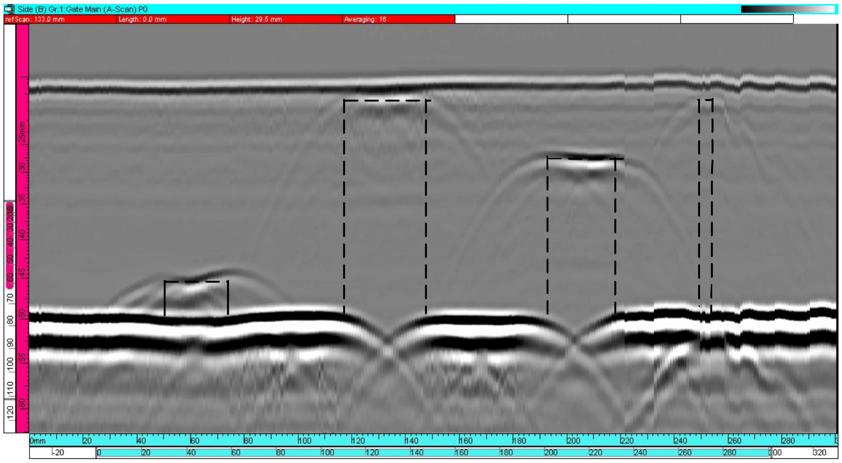
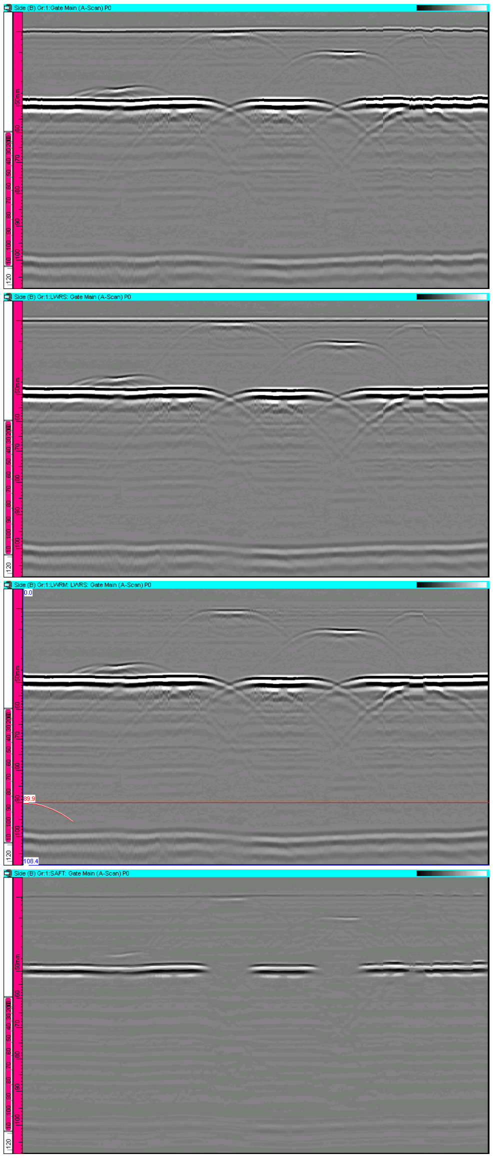


Figure 16. Superposition of notches over D-Scan image.

8. Image processing

Image processing is generally applied over TOFD images. **Figure 17** shows the most common techniques applied to enhance the indication patterns.



Original unprocessed image.

Lateral wave synchronization. Make easier to identify indications close to the upper dead zone.

Lateral Wave Removal help to confirm the presence of indications in close proximity with lateral wave.

SAFT processing makes clear the presence of ID open flaws, vanishing the "hyperbolic" arcs at flaw extremities.

Figure 17. Classical image processing applied over TOFD images.

Image processing shall be carefully applied. It is possible to partially delete actual information coming from real flaws using some algorithms as Lateral Wave Removal. Indications in the upper zone could be accidentally deleted or strongly attenuated in the process.

Conclusions

- Water wedges produce a strong SNR improvement, helping to reduce attenuation and dispersion.
- TOFD seems one of the better techniques for HDPE Butt Joints inspection
- The effectiveness of PCS selected should be experimentally checked. Recommendations based on Steel couldn't be as good as supposed to be.
- Dispersion experimented by lateral wave could be less than back wall echo and mode converted pulses, which is opposite to wave behavior in steel.
- So called dead zones should be experimentally evaluated, equations seems to be a little conservative.
- With HDPE is difficult to see the mode converted since shear waves are strongly attenuated.
- ID High height discontinuities with well separated upper and lower tip pulses could be interpreted as two non relevant separated indications, this could lead to dangerous interpretation. A supplementary signal processing SAFT technique or UT Phased Array could be necessary to discriminate.
- SAFT help to identify ID connected flaws.
- Lateral Wave Removal could confirm the presence of indications in close proximity or inside the upper dead zone.

Acknowledgements

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