TOFD technique application to examine welded joints with non-equal wall thickness of the vertical steel tanks

by D.A. Neganov 1, O. I. Filippov 2, I. I. Mikhaylov 2, A. V. Gelt 3, P. S. Golosov 4

1 Pipeline Transport Institute, LLC, Moscow, Russian Federation
2 PJSC Transneft, Moscow, Russian Federation
3 PJSC Transneft, Moscow, Russian Federation

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ABSTRACT

During construction, reconstruction and technical inspection of vertical steel tanks (VST), all wall butt welds joints are subjected to ultrasonic testing to detect internal defects or flaws. The considerable length of examined welds (it can exceed 3,000 m) necessitates the development and implementation of mechanized and automated inspection systems that can increase the rate of testing and documentation of results.

Systems of mechanized and automated ultrasonic echo-testing do not support the detection of all defect types and reliable determination of their geometric parameters. The Time-of-Flight Diffraction (TOFD) technique makes it possible to estimate the height of the defect regardless of its type and orientation. However, the application of TOFD technique for welds with non-equal wall thickness is complicated by the fact that the standard software of flaw detectors (‘depth calculator’) does not consider this non-uniformity. The authors have developed the testing procedure to overcome this limitation and to determine the depth of defects in the welds with non-equal wall thickness by TOFD technique using the standard ‘depth calculator’.

An experimental verification of this technology confirmed the correctness of the calculations. The inspection scheme and calculation of the depth of discontinuity boundaries using the TOFD technique were tested using the example of the welded joint of the walls with non-equal thickness of the 10,000-m3 tank under construction. The thickness of the walls was 12 and 14 mm; 8 and 10 mm. The inspection of the real facility has confirmed good detection of defects and high reliability of the results.

Key words: Melted joint, inspection of welded joints, TOFD, vertical steel tank, welded joints with non-equal thickness, ultrasonic testing.

INTRODUCTION

During construction, reconstruction and technical inspection of vertical steel tanks, all wall butt welds are subjected to ultrasonic testing (UT) to detect internal defects. The considerable length of examined welds (it can exceed 3,000 m) necessitates the development and implementation of mechanized and automated inspection systems that can increase the rate of testing and documentation of results.

UT is complicated by the presence of a bevel in the lower part of the weld. Bevel length can attain 10 mm or more; it does not allow to bring the sensor to the edge of the weld, decreasing the testing range in the ‘straight beam’ mode. Similar difficulties arise in tests using the ultrasonic phased arrays operating in the sectoral scanning mode.

The solution in this case can be the use of the TOFD technique in combination with other UT methods in automated or mechanized inspection. The TOFD technique is effective for testing welds of equal thickness (e.g. vertical welds). This technique is described in detail in the regulatory documents 1, 2 and in open publications 3, 4.

However, the standard software of flaw detectors designed to calculate the depth and height of defects (let’s call it the ‘depth calculator’) does not consider the possible non-equal wall thickness that makes it extremely difficult to inspect, for example, horizontal welds. In this case, the inspection of welded joints with non-equal wall thickness is possible if conducted from the inside of the tank (when the wall surfaces are on the same line). But access to the inner surface of VST is limited due to the fact that the facility is in operation. The use of the ‘depth calculator’ for inspection from the outer surface (when the wall surfaces are not on the same line) is difficult.

There are publications describing the use of the TOFD technique to inspect the complex-shaped products 5–7. Its use in the inspection of welds with non-equal thickness is also permitted by the document of the Chinese Classification Society 8.

Figure 1. Beveling option for horizontal welds of tank walls: a) sketch of beveling horizontal welded joints of tank walls, b) appearance of welded joint with beveling.

Another challenge in using the TOFD technique is due to the presence of corrosion-resistant coating of the tank. Experiments have shown that the repeated reflection of ultrasonic signals in the coating leads to an increase in their amplitude. This effect is also permitted by the document of the Chinese Classification Society 8.

The proposed solution To test the possibility of determining the defect depth in a welded joint with non-equal thickness using the signal arrival time, a ‘calculator’ was modeled that implements computations in accordance to TOFD technique principle shown in Fig. 2.

The signal travel time from the emitter to the receiver without considering the delay time in prisms will be equal to:

\[ T = \sqrt{\frac{2l_2}{V_\text{me}}} + \left( \frac{H - W_\text{th} + W_\text{th}^3}{V_\text{me}} \right)^{\frac{1}{2}}, \]  

where

\[ \begin{align*}
W_\text{th} & \text{ – the thin and thick wall thickness, respectively;} \\
W_\text{th} & \text{ – the distance from the piezoelectric transducer (TOFD) input points to the weld axis for thin and thick wall, respectively;}
\end{align*} \]

\[ \begin{align*}
H & \text{ – flaw depth;} \\
V_\text{me} & \text{ – velocity of longitudinal wave in the metal.}
\end{align*} \]

Since the software installed in general-purpose flaw detectors (built-in ‘depth calculator’) does not support the direct calculation for welded joints with non-equal thickness, the depth and height of the defect in this case was determined using Excel program.
Calculations were made for walls 12 and 16 mm thick (Fig. 3) and for input angle 60°. The depth 2/WT was selected as the cross-point of the directional pattern axes, which corresponds to the selection of the intersection point for the welded joint with equal thickness according to the EN 10863 recommendations on the TOFD configuration selection. 

The curves in Fig. 4 show the change in the depth of the defect depending on the UT signal arrival time. The estimated time does not consider the time of the signal passing through TOFD sensor prisms. 

The deep-blue curve shows the values calculated using formula (1) for the diagram in Fig. 3. Only those are shown that correspond to the parameters from 4 to 16 mm of the thick wall thickness, since the arrival time of the signals from defects located above the level of the thin wall (from 0 to 4 mm of the thick wall thickness) cannot be determined unambiguously. This is due to the fact that the signal propagates along the wall surface (side wave LW), and the shape of the outer surface has variations.

The red curve is the estimation trend obtained by the formula from EN 583-6 (standard ‘calculator’ of the flaw detector). Since different distances from TOFD probes input point to the weld axis and different wall thickness are not allowed in this case, the following assumptions were made in further calculations:

- the distance from each TOFD probe input point to the weld axis:
  \[ L = \frac{L_2 + L_1}{2} \]  (2)
- the wall thickness
  \[ WT = \frac{W_1 - W_2}{2} \]  (3)
- when determining the depth of the defect obtained by the formula from EN 583-6, WT shall be increased by the following value:
  \[ NW = \frac{W_1 + W_2}{2} \]  (4)

The green curve with correction (4) is shown in Fig. 4. Fig. 4 shows that the calculation results are almost identical in the range of wall thickness from 6 to 16 mm (green and blue curves). The ultrasonic signal duration when using the TOFD technique is about 2–2.5 oscillation periods (0.40 µs for 5 MHz frequency), which corresponds on the curve to 6...7 mm (the ‘dead zone’). This value almost completely covers the curve from 4 to 7...7.5 mm along the ordinate axis; there is a slight discrepancy (from 0.1 to 0.7 mm) in the calculation results. Due to the fact that the arrival time of the signal that passed along the upper surface of the weld depends on many factors, the authors allow the depth of the defect measuring relative to the lower surface of the weld joint.

Experimental verification

As part of the verification of the proposed solution, two samples were made that simulate welded joints with non-equal thickness: the first with a stepped configuration, the second with a smooth beveled transition from one wall to another (Fig. 5). The minimum wall thickness of the samples was 12 mm, the maximum, 16 mm. A 20 mm deep lateral hole was drilled in the stepped sample. The hole diameter was 2 mm, its center was located at 7 mm from the bottom surface.

The following equipment was used: flaw detector ‘Omniscan MX2’, TOFD probes with 5 MHz operating frequency and prisms with a longitudinal wave input angle of 60° as TOFD sensors. The following parameters were tested during the experiments:

- admissibility of changing TOFD probes location (TOFD probes-emitter – on a thin wall, TOFD probes-receiver – on a thick wall, and vice versa);
- correctness of the defect height and depth determination.

Experiments have shown the following:

1. Results of the tests carried out on both samples were similar (Fig. 6). At that, the signals from the stepped sample look ‘clearer’, because there are fewer opportunities in the subsurface zone to generate ‘phantoms’ that duplicate the main LW-signal.
2. Changing the TOFD probes position does not have a significant impact on the practical result of the test.

Fig. 7 and 8 show A-scans and TOFD-scans considering the change of the emitter and receiver positions (Fig. 8 – sample with smooth transition in the zone without drilling, Fig. 9 – same sample in the zone with lateral drilling). As one can see from the figures, the scans are almost identical in both cases. Similar results are obtained for the stepped sample.

3. The stepped sample with lateral hole was used to check the possibility of measuring the defect depth using the built-in ‘depth calculator’.

Since in all these calculations, 2/3 of the thin wall thickness was adopted as the depth of cross-point of TOFD sensors directional pattern, the input angle was 60° and the sample wall thickness was 12 and 16 mm, the calculated distances between the sensor input points and the weld axis were 15 and 24 mm. In accordance with the assumptions (2) and (3), the following input parameters were set in the flaw detector ‘calculator’:

- the distance between the TOFD sensor input points – 39 (15 + 24) mm;
- wall thickness – 14 (12 + 16) / 2 mm;
- UT signal propagation velocity in metal – 5.94 mm/µs.

Subject to the assumption (4), the correction for the depth of the defect determination is 2 mm (16 – 12) / 2.

According to the data, the ‘calculator’ showed the distance 2 mm to the front (contact) wall, and 14.1 mm to the rear wall (Fig. 9a). Based on the taken assumption (4), this distance to the front surface corresponds to the depth 4 mm (2 + 2), to the rear surface – 16.1 mm (14.1 + 2.0).

After TOFD sensors were installed in the zone with lateral hole, the signal depth was determined from the upper surface of the hole (6.3 mm) and from its lower surface (8.2 mm), Fig. 9b. Subject to the assumption (4), the depth of the defect to the upper surface of the hole was 8.3 mm (6.3 + 2.0), to the lower surface – 10.2 mm (8.2 + 2.0).

Thus, the measurement data determined that the center of the hole lies at a depth of 9.25 mm (8.3 + 10.2) / 2 that with an error of 0.25 mm coincides with its real position – 9 mm from the upper surface of the thick wall of the sample or 7 mm from its lower surface.
Application example

The proposed configuration of the weld inspection scheme and calculation of the defect depth using the TOFD probes technique was applied for horizontal welding joints of the walls of 10,000 m³ tank under construction. The wall thickness was 12 and 14 mm; 8 and 10 mm. There was no coating in the area of inspected welds.

The following equipment was used: ‘Harfang VEO’ flaw detector, TOFD with operating frequency of 10MHz and prisms with longitudinal wave input angle of 70° as TOFD sensors.

The estimated depth of the defect depending on the UT signal arrival time for the welded joint of 12–14 mm walls is shown in Fig. 10; for the welded joint of 8–10 mm walls in Fig. 11. All calculations were made considering the delay time of the UT signal in the prisms of TOFD sensors.

Examples of inspection results

Fig. 12a illustrates the TOFD-scan of the welded joint section with thickness of the welded elements 12 and 14 mm. These defects were confirmed by an ultrasonic hand scanner with two 16-element ultrasonic phased arrays with an operating frequency of 5 MHz, located to the left and right of the weld (Fig. 12b). The scan, obtained using phased arrays, is acquired with a sensitivity of 6 dB higher than the rejection level, set at a control reflector with an equivalent area of 7 mm².

The TOFD data fragment (Fig. 13a) has indications with coordinates 5,570, 5,595, 5,620 and 5,640 mm. The presence of these indications is confirmed by a manual UT scanner (Fig. 13b). The scan, obtained using phased arrays is acquired with a sensitivity of 8 dB higher than the rejection level set at a control reflector with an equivalent area of 7 mm².

Findings:
1. The TOFD technique can be used to inspect welded joints with equal and non-equal thickness from the outside of the tank wall.
2. The area between the upper surface of the thick wall and the upper surface of the thin wall cannot be accurately inspected due to the inability to describe exactly the surface profile throughout the weld.
3. To calculate the depth and height of defects, the
standard ‘depth calculator’ program (included in the software package of flaw detectors that support TOFD) can be used, provided that the following requirements and assumptions are met:

a. TOFD sensors are installed so that the cross-point of the directional pattern axes is located at a depth of 2/3 of the thickness of the thin wall from its outer surface;

b. the average distance between the TOFD input points and the weld axis for the thin and thick walls of the welded joint is taken as the distance from the input point of each TOFD to the weld axis set in the ‘depth calculator’ parameters;

c. the wall thickness in the ‘depth calculator’ is the average thickness of the thin and thick walls of the welded joint;

d. in order to obtain real values, it is necessary to add half of the delta in the wall thickness of the welded joint to the depth value obtained using the ‘depth calculator’.

Competing interests

The authors declare that there is no competing interest regarding the publication of this paper.

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