# TIME OF FLIGHT DIFFRACTION (TOFD), AN ADVANCED NON-DESTRUCTIVE TESTING TECHNIQUE FOR INSPECTION OF WELDS FOR HEAVY WALLED PRESSURE VESSELS

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**Abstract:** Time Of Flight Diffraction (TOFD) is an advanced automated computerized UT based NDT technique, used for in-service inspection of welds for heavy walled pressure vessels. TOFD system is capable to scan, store and evaluate flaw indications in terms of height, length and position with greater accuracy and is suitable for weld thickness ranging from 1" to 16".

TOFD technique is based on diffraction of ultrasonic waves on the tips of discontinuities instead of reflection on the interface of discontinuities. When ultrasound is incident at linear discontinuities such as crack diffraction takes place at its extremities in addition to the usual reflected wave. The diffracted energy is emitted over a wide angular range, presumed to originate at the extremities of the flaw.

Scanning is done externally parallel to weld axis using longitudinal probes with incidence angle range of 45° to 70° and when flaw is detected scanning in perpendicular direction for better evaluation of flaw. Signals from the upper and lower tips of the flaw are displayed as D-Scan image.

Recently, the author had witnessed TOFD conducted by M/s. Japan Steel Works in India at Indian Oil Corporation, Gujarat Refinery for 2 Nos. in-service hydro-cracker reactor of 223 mm thickness after 10 years service.

ASME had approved TOFD for ultrasonic examination of welds and in lieu of RT for thickness over 4". British Standards Institute had formulated Standard BS: 7706 - 1993 for TOFD.
TOFD benefits include real time weld integrity assessment, higher accuracy in flaw detection/sizing and digitized storage of TOFD records.

Insensitiveness to surface defects upto ½" deep, high cost and the need of experienced operator are limitations of TOFD.

**Introduction:** Weld Inspection is a field where various forms of inspection techniques are adopted for the weld integrity assessment and Non-Destructive Testing (NDT) is one of them. Under ASME Boiler and Pressure Vessel Code Section V, the American Society of Mechanical Engineers (ASME) recognizes different NDT methods such as Penetrant Testing (PT), Magnetic Particles Testing (MT), Ultrasonic Testing (UT), Radiography Testing (RT), Acoustic Emission Testing (AE), Leak Testing (LT) and Visual Testing (VT) [1].

Ultrasonic testing in NDT is one of the largest applications in weld inspection. Techniques vary according to weld material, weld thickness, and weld process and even Code requirements. The conventional pulse echo based UT requires manual interpretation in flaw detection and sizing, which might end up with human errors. In response to the demand for better sizing of defects an advanced ultrasonic weld inspection was developed in the 1970's with the introduction of Time Of Flight Diffraction (TOFD) [2].
The TOFD technique was first applied in 1985 at the Harwell Center (UK) in response to insistent requests to size cracks in nuclear reactor welds [3]. Maurice Silk had invented the TOFD in the late 1970's [13].

TOFD System: The TOFD technique is a fully computerized and automated system able to scan, store, and evaluate indications in terms of height, length, and position with a grade of accuracy never achieved by other ultrasonic techniques [4]. TOFD system consists of UT detector (Computer), transmitter, receiver, pre-amplifier, encoder and cables [5]. TOFD system is small, light, portable and accessible to inspection position (Fig. 1).

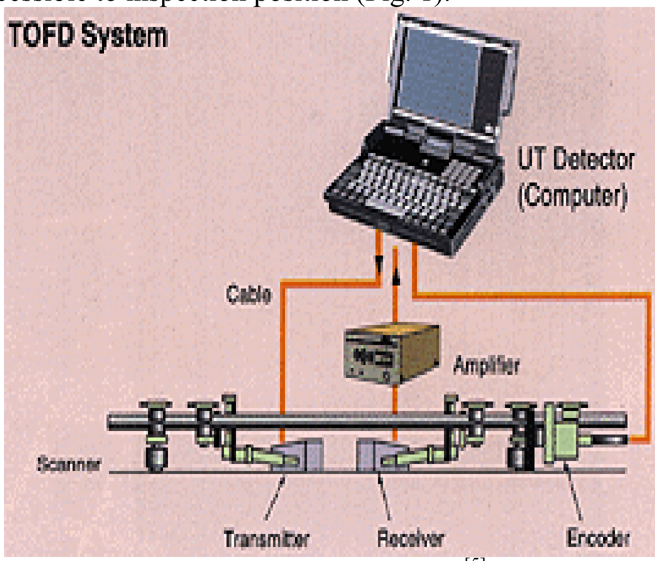


Fig. 1 Typical TOFD System [5]

The principle and operation of TOFD: The TOFD technique is based on diffraction of ultrasonic waves on tips of discontinuities, instead of geometrical reflection on the interface of the discontinuities [4].

When ultrasound is incident at linear discontinuity such as a crack, diffraction takes place at its extremities in addition to the normal reflected wave. This diffracted energy is emitted over a wide angular range and is assumed to originate at the extremities of the flaw (Fig.2). The conventional UT relies on the amount of energy reflected by the discontinuities [2].

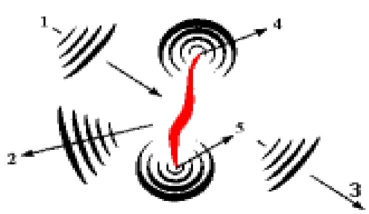


Fig. 2 Principle of Time of Flight Diffraction (TOFD) [6]

Legend: 1 - Transmitted wave 2 - Reflected wave 3 - Through transmitted wave
4 - Diffracted wave at upper crack tip 5 - Diffracted wave at lower crack tip

In addition to energies diffracted by defects, the TOFD method will also detect a surface (lateral) wave travelling directly between the probes and also a back wall echo from energies that reach the back of the test piece without interference from defects [2].
The TOFD technique uses a pair of probes in a transmitter-receiver arrangement (Fig. 3). Usually longitudinal probes are applied with an angle of incidence range of 45° to 70°. The diffracted signals are received via the receiver probe and are evaluated with the Ultrasonic System [2]. The

difference in the flight of the diffracted wave fronts carry the information on the spatial relationship of the tips of the defect and hence the extent of the defect [14]. TOFD method only evaluates diffracted echoes, which are 20dB less than the reflected echoes [13].

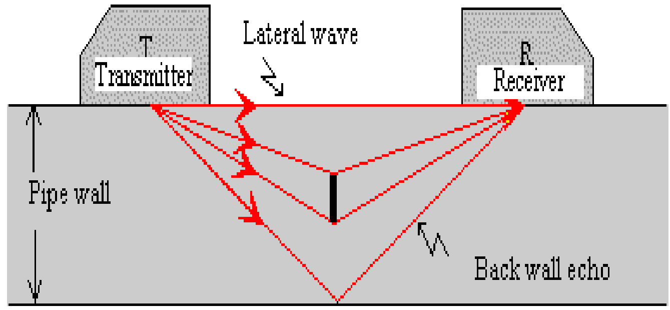


Fig. 3 Transmitter-Receiver arrangement of TOFD [7]

Gray scale imaging techniques are applied to the RF (AC) signal phases and enable weld integrity to be observed in real time. The defects are shown like as shell pattern on CRT. A-scan signals are stored in the memory together with location signals [5] (Fig. 4) [7].

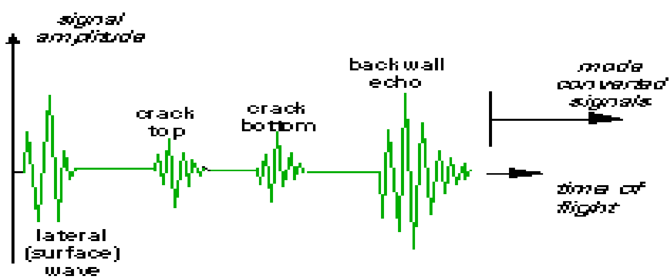


Fig. 4 - schematic of TOFD
A-scan

Scanning is carried out externally by placing the two probes located at equidistant over the weld centre. The scanned image is often referred to as D-Scan (Fig. 5) [7].

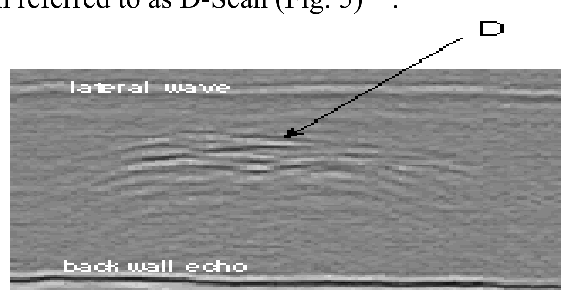


Fig. 5 - TOFD D-scan of butt weld
and defect

Scanning has to be done by moving the probe-holder in the direction parallel to the weld axis. When a flaw is detected, the scanning is done perpendicular to the weld axis for the better evaluation of size and dimensions of the flaw [4] (Fig. 6).

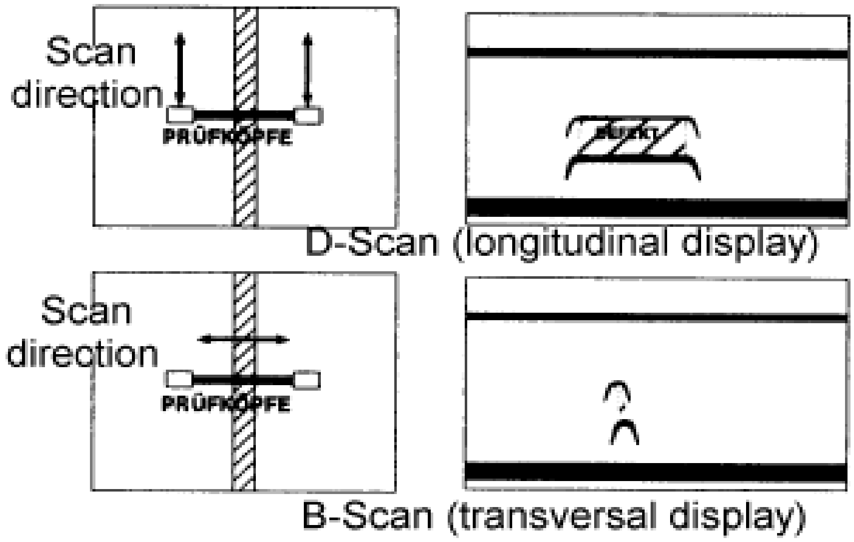

Fig. 6 Scanning of weld in parallel and perpendicular direction to weld axis [6]

With a time of flight of each flight path, the ultrasonic velocity and the spatial relationships of the two probes, location and height of defects can be very accurately calculated [5].

**Results:** Being the recent application of TOFD in India during August 2003, the author had witnessed the TOFD technique conducted in India at Indian Oil Corporation Ltd, Gujarat Refinery, Vadodara for their 2 Nos. in-service hydro-cracker reactors (06-RB-001 & 002) which is a high walled pressure vessel having a thickness of 223 mm and of size 25.5 m Height X 3.3 m Diameter conforming to 2 ¼ Cr 1 Mo (SA 336) designed for an operating pressure of 170 kg/cm2 and operating Temperature of 413º C. These reactors were put into service in 1993 and TOFD was done after 10 years of life to assess the weld integrity of the reactor [8].

M/s. The Japan Steel Works, Japan had done the TOFD at an approximate cost of Indian Rupees 40 lakhs (about 91,00,000 Yen) [8]. The TOFD Equipment used was Micro Tomoscan (RD Tech Canada - Cost US $200K approx.) having the built-in software Tomo View Version 1.4 R6 of NICCO Inspection Service (on-line-configuration). Presently, there is powerful and versatile software Tomoview 2 available from R/D Tech [17]. Two pairs of 45º and 60º probes of 5 MHz each were used for both transmitters and receivers (The equipment has provision for using 6 pairs of probes). The weld was divided into segments of 500 mm each for the scanning [9].

TOFD has now been demonstrated on a thick section (350 mm) qualification block, to meet the requirements of ASME Code Case 2235, Use of ultrasonic examination in lieu of radiography, Section 1/711, Divisions 1 and 2 which became effective in 1996 [15].

**Discussion:** The TOFD technique can be depicted in a mathematical model (Fig.7). Assuming that the defect is oriented in a plane perpendicular to both the inspection surface & the line joining transmitter as well as receiver along the inspection surface and that the defect is midway between the transmitter & receiver, Pythagoras's theorem will be useful in sizing the defect. If the position of the defect below the inspection surface is at a depth D mm, the distance of the two probes separation is taken S mm, the length of the defect is L mm, the thickness of the steel plate is H mm and the speed of propagation of sound waves is C, then the arrival times of the various signals are will be as follows based on the mathematical model of TOFD [13]:

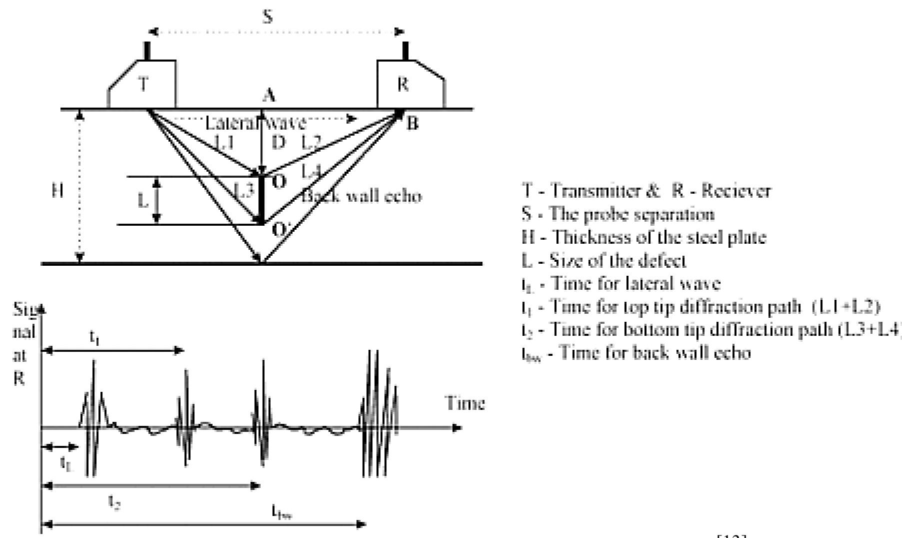


Fig. 7 Mathematical Model of TOFD Technique [13]

The first arrival time from the lateral wave (L) signal to the receiver:

$$t_L = \frac{S}{C} \;\ldots\ldots(1)$$

The second arrival time from the top tip diffracted ($t_1$) signal to the receiver:

$$t_1 = \frac{\sqrt{4D^2 + S^2}}{C}\ldots\ldots\ldots(2)$$

The third arrival time from the bottom tip diffracted ($t_2$) signal to the receiver:

$$t_2 = \frac{\sqrt{4(D+L)^2 + S^2}}{C}\ldots\ldots\ldots(3)$$

The fourth arrival time from the back wall echo ($t_{bw}$) to the receiver:

$$t_{bw} = \frac{\sqrt{4H^2 + S^2}}{C}\ldots\ldots\ldots(4)$$

The value of the depth D is from the equation 2:

$$D = \frac{1}{2}\sqrt{C^2 t_1^2 - S^2} \;\ldots\ldots(5)$$

The value of the defect size L is from the equation 3:

$$D = \frac{1}{2}\sqrt{C^2 t_2^2 - S^2} - D\ldots\ldots(6)$$

The value of the thickness of the plate H is from the equation 4:

$$H = \frac{1}{2}\sqrt{C^2 t_{bw}^2 - S^2} \;\ldots\ldots(7)$$

The value of the separation of the probes S is from the equation 4:

$$S = \sqrt{C^2 t_{\delta w}^2 - 4H^2} \;......(8)$$

TOFD is having application in two areas namely "In-service defect monitoring of critical equipments" and "Defect detection, documentation and evaluation during the production" [6].

Companies like Exxon, Shell, Fluor Daniel, Texaco, Chevron, Kobe Steel (Fig.8) etc. are using TOFD in lieu of RT for inspection of welds of heavy wall pressure vessels [4,5].

Fig. 8 TOFD being done for a heavy walled pressure vessel at shop [5]

Recognition and Standards for TOFD: TOFD is having the recognition from International bodies.

The British Standard Institute has issued a TOFD standard BS: 7706 -1993, which provides guidance on the application of TOFD technique for the detection, location and sizing of flaws in materials. It may be expanded to cover other important applications of TOFD [10].

There is a European TOFD standard draft ENV 583-6 Non-destructive testing - Ultrasonic examination part 6 - Time of Flight diffraction technique as a method for defect detection and sizing [16].

Maurice Silk has drafted the British Standard BS-7706 and the first draft of the European Standard ENV-583 Part 6 [15]

Though all the butt welds of high pressure vessels manufactured in accordance with ASME Section VIII.DIV.2 should be inspected by using RT for quality assurance, the ASME Code Case No.2235 permits automatic UT in lieu of RT for thickness over 4” [4,5,11].

ASME Code has included in Section V Article 4 Appendix E, the computerized ultrasonic system and TOFD technique for ultrasonic examination of welds [4,12].

Advantages of TOFD: There are many advantages for using TOFD for weld inspection.

1. High Probability of Flaw Detection (POD) [5].
2. Lower False Call Rates (FCRs)
3. High Accuracy of Flaw Location Measurement [5].
4. High Accuracy of Flaw Sizing in Length [5].
5. Weld Integrity can be assessed on CRT in Real Time as probes scan and acquisition of data [5].
6. All inspection Results/Data is Digitized and Stored so that the same can be Recalled and Processed for In-Service Inspection [5].
7. In-service inspection avoids production loss.
8. As TOFD is a substitute for radiography, production is not interrupted since evacuation of areas is not necessary [6].
9. Since the equipment is portable, it is possible to perform TOFD on all feasibly accessible areas [5].
10. TOFD saves costs, if applied during construction, since it is possible to distinguish between pre-service and in-service defects. That means the unit can stay longer in production, and is safe [6].
11. By automatic system with the aid of computer and advanced soft wares it is possible to evaluate signals very rapidly [6].
12. Most efficient for inspection of thick-walled vessels where X & Gamma ray would require too much time [13].

Limitations of TOFD: TOFD suffers from certain limitations.

1. TOFD is insensitive to surface defects upto ½” deep [6,9]. However, R/D Tech’s equipment allows simultaneous combination of TOFD with pulse-echo, which complements TOFD and covers the dead zones [17]. Also, Sonomatic Microplus of AEA Technology have succeeded in reducing the dead zone to 2 mm.
2. For TOFD the gain must be very high, which produces a very high back wall echo and it is not suitable for coarse-grained materials [13].
3. TOD Technique is not effective at detecting and sizing defect lying parallel to the inspection surface [13].
4. High initial cost of TOFD Equipment.
5. The need of experienced and skilled operator.

**Conclusions:** Despite few drawbacks, the Time Of Flight Diffraction (TOFD) technique is a rapid, versatile, reliable and an effective advanced UT based NDT method for inspection of welds especially for heavy walled pressure vessels (both pre-service and in-service) aimed at better flaw detection and accurate evaluation of flaw location and flaw sizing with real time weld integrity assessment and acquisition of data to be stored for future inspection reference. With the recognition from international bodies like ASME, BSI etc TOFD will gain much more importance across the globe and will be applied for weld inspection very widely in the future.

With a view to adopt this new NDT technique, Kochi Refineries Ltd (KRL) has chalked out an action plan for the in-service inspection of their Reactors in Diesel Hydro De-Sulpurisation (DHDS) unit using TOFD in the year 2010 when these reactors will attain a life of 10 years.

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