Developments in Time-Of-Flight Diffraction (TOFD)

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Abstract
Time-Of-Flight Diffraction (or TOFD, as it is widely known) has been developed for a number of years; however, there is still potential for improvement, from reducing dead zones to characterizing defects to more accurate sizing. This presentation will describe the TOFD technique as currently known, plus the subsequent developments available (lateral wave straightening, lateral wave removal, synthetic aperture focusing). Then, a new, improved sizing approach will be described, which uses a double filtering technique adapted from geophysics. This involves Weiner filtering to tidy up the signal, followed by autoregressive spectral extrapolation. Some preliminary TOFD results will be shown on a standard cracked block.

Keywords: TOFD (Time-Of-Flight Diffraction), digital signal processing, improved sizing, double filtering technique

1. Introduction

TOFD (Time-Of-Flight Diffraction) was developed by the UKAEA Harwell (now AEA Technologies) in the late 1970’s by Maurice Silk and associates (1). Harwell developed an early automated ultrasonic system called Zipscan, which used signal averaging to improve the signal-to-noise ratio. TOFD came to the fore during the nuclear PISC II and DDT trials (2, 3), where it showed not only good detection (especially in the midwall regions), but also significantly better sizing than conventional UT (see Figure 1).

Figure 1: Left, defect sizing in DDT Trial plate 1 using all UT techniques; right, defect sizing using TOFD alone.
Since the early 1980’s, TOFD has become standard practice in the nuclear industry. In the last decade or two, TOFD has also penetrated the petrochemical and other industries, though using linear scanning – not raster scanning as in nuclear.

2. What is TOFD?

Diffraction is a general phenomenon in ultrasonics, as normal in wave physics. The tips of internal defects will diffract an ultrasound beam; this diffracted beam can then be detected and the arrival time accurately measured. The “standard” TOFD set-up is shown in Figure 2.

TOFD normally uses a pitch-catch arrangement with the probes symmetrically spaced across the weld. The wedges are angled to generate wide-angle, longitudinal waves (or L-waves), since these arrive first and don’t confuse the interpretation. (Shear waves are also generated, and can be viewed if required by extending the gate). Four types of signals are detected:

- The Lateral wave: A sub-near-surface longitudinal wave generated from the wide beam of the transducer.
- The Backwall reflection: A longitudinal wave reflected from the back wall
- The Reflected wave: A longitudinal wave reflected by a lamellar planar defect
- The Tip Diffracted wave: A circular longitudinal (or L-wave) diffracted by the edge of a defect.

The lateral, backwall and tip-diffracted waves are visible in Figure 2.

3. Advantages of TOFD

TOFD is a very powerful technique, and allows:
1. Good midwall defect detection.
2. Accurate sizing of defects using the times of arrival of diffracted signals.
3. Defect detection even if defects are mis-oriented or located away from the weld centreline.
4. Rapid linear scanning (raster scanning not required)
5. Non-amplitude scanning and detection.
6. Set-up independent of weld configuration.

TOFD is very fast and economical; one transducer pair covers up to 50 mm (2”) or more of wall thickness in a single pass. For thicker sections, more TOFD pairs are required. Alternatively, multiple TOFD transducer pairs can be used on sections less than 50 mm thick to provide increased Probability of Detection and/or improved defect positioning.

4. Limitations of TOFD

The limitations of TOFD can be summarized below:

1. Dead zone at top surface (OD).
2. Dead zone at bottom surface (ID).
3. Sensitive to very small defects with a risk of false calls if not combined with pulse echo.
4. Analysis can be difficult, so specialist interpretation required.
5. Some sizing errors are possible from lateral position of defect.

The main TOFD limitation is the dead zones. TOFD has two dead zones (ID and OD) where defects are typically not detected. These two dead zones are located near the Lateral Wave and near the Backwall reflection. The depth of these two dead zones depends on the TOFD configuration, frequency and damping. For example, at 7.5 MHz, the lateral wave (OD) dead zone is around 3 mm, while the backwall (ID) dead zone is ~1 mm. Lower frequencies and less transducer damping will generate bigger dead zones, while higher frequencies and increased damping produce smaller dead zones. TOFD frequencies are normally a few MHz higher than pulse echo frequencies; for example, AUT on pipelines may use 7.5 MHz for (shear wave) pulse-echo, while 10 MHz can be used for (longitudinal wave) TOFD.

To get full 100 % coverage, TOFD should be combined with the Pulse Echo technique. Pulse-echo has high defect detection rates for surface-breaking and near surface defects, but is poor on midwall defect detection. Conveniently, TOFD and PE are complementary; the strong features of pulse-echo are the weak points of TOFD, and vice versa.

5. Diffraction Imaging

Diffraction is a general ultrasonic phenomenon, and occurs under much broader conditions than just longitudinal-longitudinal diffraction as used in standard TOFD. Other possibilities include:

- Shear-shear diffraction
- Longitudinal-shear diffraction
• Single transducer diffraction (called “back diffraction” or the “tip echo method” in Japan)
• Twin transducer TOFD with both transducers on the same side of the defect/weld.
• Complex inspections, e.g. nozzles.

However, TOFD refers to a specific application of ultrasonic diffraction: two longitudinal wave transducers in pitch-catch arrangement with broad beams. TOFD images look like vertical through-sections of the weld. The lateral wave is essentially the OD; the backwall is essentially the ID; and any defects show as tip diffracted signals between these two. Figure 3 shows a typical example.

Figure 3: Typical TOFD image showing lateral wave (OD), backwall (ID) and four labelled defects.

TOFD images always use gray scale presentations and full RF waveforms to capture the phase information. As shown in Figure 2, signals are identifiable by their phase. The OD and ID have a phase reversal, as do the top and bottom of defects.

6. Defect Depth Measurement

While defects can be detected by signals on the screen, or perturbations of the lateral and backwall, sizing is more complicated. If the defects are small (i.e. less than the ringing of the signal or ~3 mm), then it is not possible to differentiate the top and bottom signals. If the top and bottom diffracted signals can be reliably differentiated, then sizing requires cursors to measure the time of arrivals, and standard math formulae to calculate depth (see Figure 4). Figure 5 shows a standard approach for setting cursor positions for sizing.
Figure 4: Standard geometric analysis of defects using TOFD

\[ d = \sqrt{\left(\frac{c}{2}\right)^2 \cdot (t - 2t_0)^2 - S^2} \]

Figure 5: Cursor positions for defect analysis.

\[ h = d_2 - d_1 \]

\[ t_1, t_2 \Rightarrow d_1, d_2 \text{ and } h \text{ are automatically calculated} \]
7. TOFD Processing Techniques

In addition to accurate sizing and detecting off-axis defects, various processing techniques can be used for TOFD: lateral wave straightening; lateral wave removal; SAFT (Synthetic Aperture Focusing Technique). These examples are compared in Figure 6 below.

![Figure 6: Left, TOFD image as recorded; middle left, lateral wave straightened; middle right, lateral wave removed; right, after SAFT-ing.](image)

These treatments can improve the TOFD images significantly; however, they do not address one of the more important aspects of TOFD – the sizing limitations due to dead zones or just “readability”. These are addressed later after Codes.

8. Misoriented Defects

Another study was performed on a selection of defects to determine how critical the effects of mis-orientation are (4). The theoretical calculations (shown in Figure 7) indicated that TOFD was far less sensitive to mis-orientation than pulse echo.
The experimental results are shown below at four selected angles.

Figure 8: Sample TOFD scans at various angles. Top left, 0 degrees; top right, 10 degrees off axis; bottom left, 25 degrees, bottom right, 45 degrees.

Basically, these results show that TOFD is effectively independent of incident angle, and certainly within the range provided by pulse echo.

9. Codes

At the time of writing, the ASTM TOFD ASTM E-2373-04 has been published (5). ASME has a published TOFD code (6). ASME has approved a TOFD Interpretation Manual, NonMandatory Appendix N (7), and also a NonMandatory TOFD Guideline for
set-ups. There are two European “guides”, BS7709 and EN583_6 (8, 9). Overall, TOFD codes are quite extensive and cover most aspects of the technique.

10. New Developments in TOFD

Besides the standard techniques of scanning and improving the images, Olympus has been working with the University of Toronto to improve the “readability” of TOFD (and back diffraction) signals, with some success. The early back diffraction S-scan studies were performed using manual scanning, and produced encouraging results (10). These used a combined Wiener filter and autoregressive spectral extrapolation technique (now patented).

A slightly modified (and confidential) digital signal processing filtering technique has been applied to the TOFD signals. The objective here has been to minimize the dead zones, while also making the signals more accurate. Figure 9 shows an example of the TOFD scan before with three defects ringed. The processed version is shown in Figure 10, and distinct improvements in readability are clear. Notice the improvement in the “shrunken” lateral wave for an immediate comparison.

![Figure 9: Sample TOFD scans before using DSP approach on standard defects.](image-url)
Figure 10 shows an example of the scan using an alternative approach to processing.  

Note that this DSP technique can generate some additional signals. Specifically, Figure 11a shows an example of the original waveform around location 450, while Figure 11b shows an example of the same waveform after DSP. Lower amplitude additional signals are clearly visible, though efforts are currently being made to eliminate them. However, the results are significantly more “readable” than with standard TOFD.

Figure 11: Left, waveform before processing. Right, after processing with additional signals present.

11. Conclusions

1. TOFD (Time-Of-Flight Diffraction) offers major advantages for inspecting welds and related components.

2. TOFD is a powerful technique, and allows good midwall defect detection, accurate sizing, detection of mis-oriented defects, and fast linear scanning.

3. Like all inspection techniques, TOFD has limitations that the inspector should be aware of. The primary concern is the two dead zones (ID and OD) where defects are typically not detected. Sizing is also limited to $\pm 3$ mm or so.
4. Current R&D work is focusing on reducing these dead zones and improving readability as much as possible.

References