CRITICAL EVALUATION OF TOFD FOR SEARCH SCANNING

J.M. Farley, N.S. Goujon, B.W.O. Shepherd
Mitsui Babcock, Renfrew, UK

Abstract: The Time of Flight Diffraction (TOFD) technique was originally developed as an accurate method for measuring the throughwall dimension of defects detected by other methods. However it is increasingly being used for detection, as well as for sizing.

The diffracted signals from defects can be significantly weaker than conventional reflected signals and although previous blind trials have concluded that TOFD detection capability is good, the participants would presumably have been expecting defects to be present. Work has been therefore been performed to determine the extent to which defects can be missed when using TOFD as a stand-alone search method under more realistic conditions.

Testpieces containing real and simulated cracks were used to assess reliability of TOFD for defect detection, concentrating on situations where weaknesses were suspected. Objective assessment of defect detectability was carried out initially through open trials on selected samples. The personnel who performed these trials had details of the defects present.

Using the results from the above samples, blind trials samples were designed and manufactured. The appearance of these manufactured samples was similar to specimens cut from vessels or pipes which had been in-service. Three different companies then inspected the testpieces using TOFD. These companies were not told that these were blind trials.

A significant number of defects were not reported or were misinterpreted.

The results suggest that, even if TOFD is a good complementary NDT technique for defect detection, there are circumstances where it should not be used as a stand-alone search method.

Introduction: The ultrasonic Time of Flight Diffraction (TOFD) technique was originally developed for use within the nuclear industry by Silk and Lidington (1975) thirty years ago as an accurate method of sizing defects.

TOFD differs from conventional PE examinations in that the reflected energy compared with a reference reflector is not used for the classification of defects, but the actual size, derived from the diffracted signals generated in all directions at the extremities of the defect. With the knowledge of the wave velocity and the spatial relationships of a pair of probes, the positions of the tips of the flaw can be calculated very accurately.

TOFD has been reported as being a technique with high probability of detection for both planar and volumetric defects and of excellent reproducibility and accuracy. The success in this field, combined with strong advertising of cheaper and more portable TOFD hardware, has resulted in its adoption within a wide range of industrial sectors (offshore, petrochemical, chemical, defence, conventional power generation). It is increasingly being proposed as a rapid search tool.

Published trials of TOFD and comparison with other NDT methods (manual pulse-echo, automated pulse-echo, radiography) have generally indicated acceptable TOFD capability for both detection and sizing. However, these trials have tended to be on a variety of defect types to provide a general overview of capability, rather than to investigate where there may be systematic weaknesses in TOFD.

This paper covers the work performed on a Project entitled “Critical Evaluation of TOFD for Search Scanning” conducted by Mitsui Babcock and sponsored by the UK Health and Safety Executive (HSE). The objective was to identify if critical defects could be missed when Time of Flight Diffraction (TOFD) technique was used as a rapid NDT search technique. The project brought together a literature survey, theoretical studies, open-trials (in-house) and blind trials (external). Blind trials were carried out by personnel who were not told that defects were present in the samples and who were not informed that the work they were performing was a blind trial. The reason for not revealing to the inspection teams that they were participating in blind trials is that TOFD signals are often significantly weaker than PE signals. The defect images may therefore not be very apparent particularly when there are other background reflections, and it was considered important to avoid raising the degree of "vigilance" in data interpretation compared to that which would normally be the case for shop floor or site inspections.

Results: Literature Review and Theoretical Modelling of TOFD: A literature review of existing data on TOFD capability and a theoretical modelling of the TOFD technique were carried out to identify possible systematic weaknesses of the technique. The results from this review revealed some weaknesses, some of which are:

- Existence of a zone with reduced detection capability of the order of 2-3mm below the scanning surface. This problem also occurs at the back-wall but the extent of the zone may vary.
- Setting of an adequate sensitivity is essential to enable the detection of weak defect signals and at the same time avoid overloading the system with irrelevant signals.
- The possibility of defects masked by other defects or due to the geometry: defects symmetrical around the scanning axis at the same position along the weld (only one of the defects might be reported whereas both would be detected by pulse - echo), defects masked by a large area of porosity, small cracks at the back-wall region, etc.
- TOFD can be limited by the geometry of the sample or by an obstruction limiting the scanning area e.g. ends of longitudinal seams adjacent to circumferential seams (require grinding).
- TOFD signals may be missed during analysis since they are often weaker than pulse-echo signals (this can be a particular problem if a "noisy" image is produced due to the presence of small defects such as slag, porosity, etc.)
- TOFD signals from defects offset from the centre line can be obscured within the back-wall signal possibly hindering detection.

Results: Open Trials: The samples were three carbon steel butt weld test-samples 20mm, 40mm and 60mm thick each containing five embedded fatigue cracks positioned on the weld centre line with sizes (mechanical measurements given by the manufacturer, confirmed by pulse echo UT) given in Table 1:

Sample No		Size (mm)	Defect 1	Defect 2	Defect 3	Defect 4	Defect 5
	1	Length	8	12	20	32	40
		Depth	2	3	5	8	10
	2	Length	8	16	32	40	48
		Depth	2	4	8	10	12
	3	Length	8	16	32	48	60
		Depth	2	4	8	12	15

Table 1: Defects characteristics

Different probe angles (45º and 60º), probe frequency (2MHz, 5MHz and 10Mhz) and probe arrangements (variable probe centre separation to focus around the defect area) were used to optimise the scan configuration. It was found that the different arrangements did not significantly influence the defect size measurement, but made a difference to detection. The results given in the following tables were obtained using the optimised scan configuration (probes and probe centre separation).

The results from these Open Trial test-samples can be summarised as follows:

- The signals from the fatigue crack defects were weak

- None of the 2mm deep defects were detected
- Defects having a depth of approximately 4mm and less were difficult to identify and to size, and may not have been detected if the operator was unaware of their presence.
- The shapes of the signals from the shallower defects were very similar to those from point reflectors and could therefore be easily misinterpreted.
- Open cracks in the root area are usually illustrated when the back-wall signal appears segmented. The presence of the weld root in both of the test samples prevented a clear break of the back-wall signal, with the exception of the larger defects (defects No. 5). Indications of the presence of the defects are given by the waves arising after the back-wall echoes, but the shallower defects can still be misinterpreted as point reflectors.

Results – Blind Trials: The blind trials test-samples were designed to contain defects that might be difficult to detect because of their position or their nature. They contained defects such as root cracks some of which may be obscured by porosity, symmetrical defects positioned on the fusion face at the same position along the weld and defects offset from the weld centreline. Mis-aligned joints were also addressed as the mismatch might obscure root cracks. The welds were tested in the as-welded condition.

Blind trials were organised by the Health and Safety Laboratory (HSL) and performed by three teams at their premises. The companies were not informed that the exercise was a blind trial. The results are summarised in Table 2 and illustrated by Chart 1.

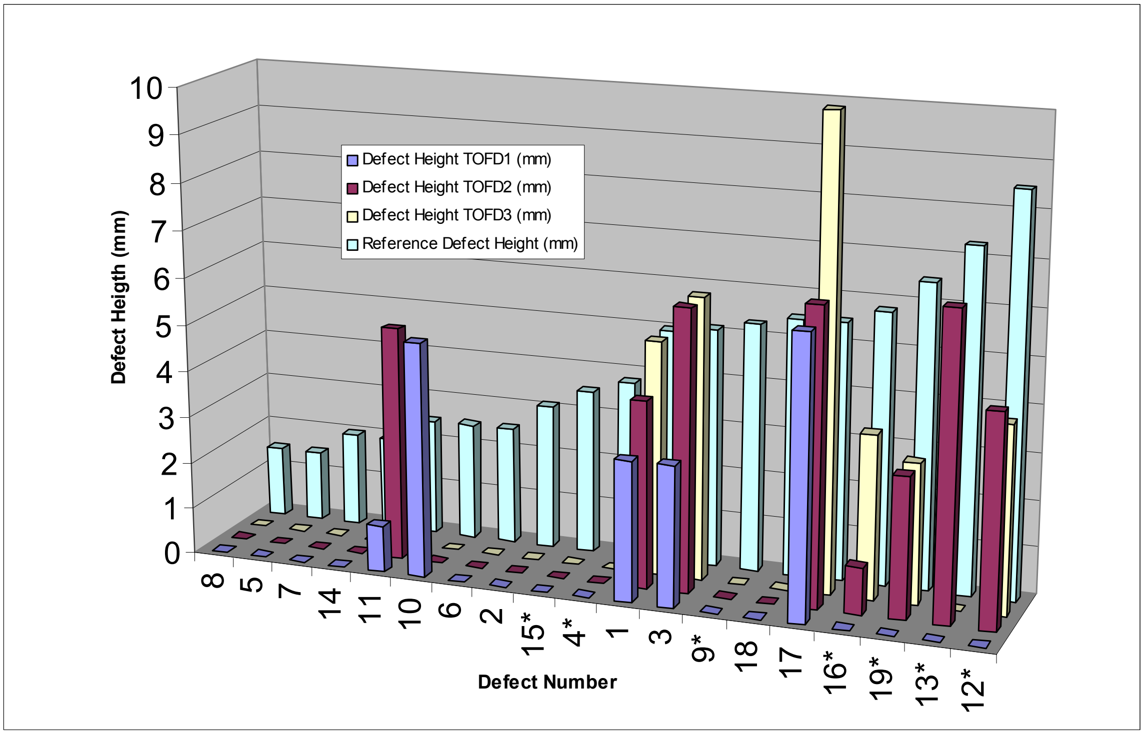
Defect Type	Ref No	Detected (0, 1, 2 or3)	Defect Height (depth) mm		Defect Length mm		Obscuration*	Interpreted as
			Reference	Reported	Reference	Reported		
Root or inner surface Cracks	1	3	5	3 (17-20) 4 5 (15)	30	400 150 32	M + P	Defect associate with root defect Surface breaking defect Internal surface breaking defect
	3	3	5	3 (17-20) 6 (14) 6 (14)	30	400 27 30	M + P	Defect associate with root defect Reflective signal Internal surface breaking defect
	4	0	3.5	-	15	-	M + P	-
	9	0	5	-	30	-	M + P	-
	12	2	6	4.5 (30.5) 4 (31)	30	35 42	NO	Indication Internal surface breaking defect
	14	0	2	-	8 (28)	-	NO**	-
	15	0	4	-	16 (30)	-	NO**	-
	16	2	5	- 3.5 (36.5)	15	20 11	NO	Disturbance at the back-wall Internal surface breaking defect
Root Defect	5	0	1.5	-	25	-	M	-
	7	0	2	-	15	-	M + P	-
	8	0	1.5	-	13	-	M + P	-
Mid-wall Crack	19	2	6	3 (13-16) 3 (15)	50	45 14	P	Indication Lack of Side Wall Fusion
Surface Breaking Crack	2	0	3	-	15	-	M	-
	13	1	6	6.5	30	52	NO	External Surface breaking
LoSWF	6	0	2.5	-	20	-	M	-
	10	1	2.5	4	10	15	P	Lack of fusion
	11	2	2.5	(23) (30)	5	6 20	P	Indication Slag/porosity
	17	3	5.5	(11-17) 6.3 (10.2-16.2) 10 (9)	150	270 170 157	P + D	Lack of Side wall fusion Lack of Side wall fusion Lack of Side wall fusion
	18	0	5.5	-	50	-	D	-

NO=No Obscuration P=Porosity D=Other Defect M=Misalignment

* Defects 12, 13 & 16 were offset from the weld centreline

** The presence of a backing plate may have been confusing

Table 2: Blind Trial Results – Summary Table



Note: 1mm is used when the defect is reported but no height is given

* height value from sectioning

Chart 1: Blind trial results – defects height measurement

From the 19 defects of interest, TOFD Team 1 reported 26% of the defects, TOFD Team 2 reported 42% of the defects and TOFD Team 3 reported 32% of the defects.

Only two defects below 5mm depth were reported, both defects are lack of sidewall fusion defects of 2.5mm height (these defects were not intended). One of the defects was only reported by one team who correctly interpreted the defect. The other defect was reported by two teams but was reported as an indication by one team and as slag/porosity by the other. Nine of the defects were 5 to 6mm high. One of the teams only correctly reported one of these nine defects, the two other defects reported by this team were interpreted as defect associated with root area and were oversized in length (they reported the indications over most of the weld length). Team 2 reported 78% of these defects and Team 3 reported 67% of these defects.

Defect 12 (an 8.5mm internal surface breaking crack) was detected by two of the three teams but both reported it as less than 5mm. Defect 13 (a 7.3mm external surface breaking crack) was only reported by one team.

Chart 1 illustrates the findings on the height measurement of the defects reported collected during the blind trials for all the major defects. Where defect height is represented as 0 mm, this means the defect was not reported.

58% of the defects implanted into the test-samples were root defects (mainly root cracks). If the analysis focuses on that type of defects it is clear from the results that none of the defects of reference height below 5mm were detected. One out of the four 5mm height root cracks was not detected and from the three detected; only one of the three teams interpreted the defects as root cracks. The larger root crack (6mm reference depth) was reported by only two of the teams and was in both cases undersized; one of the teams interpreted the defect as an internal surface-breaking defect and the other only reported the presence of an indication.

The presence of porosity around a defect does not appear to prevent the detection of a defect. However, in many cases, especially when the porosity density is high, the defects were misinterpreted and their length over-estimated.

Defect No18, which was shorter but similar in height and position to defect No 17, was not reported. This result confirms the limitation of TOFD during search scanning not be able to detect defects masked by other defects (only one of the defects was reported whereas both were detected by pulse-echo).

One of the internal surface breaking defects, defect No16, was intentionally implanted away from the weld centreline. The defect has a 5.8mm depth and no porosity or other defect that could have prevented its detection was present. Team 1 did not report the defect, Team 2 reported disturbance at the back-wall but did not provide the defect height (1mm height was used on the charts to illustrate that the defect was detected) and Team 3 reported it as a surface breaking defect 36.5mm (parent material 40mm thick) from the scanning surface and 11mm long. Similarly, defects No12 & No13 which are both offset from the weld centreline were not reported by all the teams. This result complements the theoretical work and the open trials: defects offset from the centreline can be missed if the scan line only corresponds to the weld centreline.

Conclusions: The results of this study indicate that although TOFD is a good complementary NDT technique for defect detection and sizing there are circumstances when it should not be used on its own. If used alone as a rapid search scan there is the risk that critical defects could be missed.

The open trials demonstrated that certain types and locations of flaw are very likely to be missed. The blind trials detection rates were 26%, 42% and 32% for the three teams. None of the intended defects below 5mm were reported. For nine defects in the 5mm to 8mm range the detection rates were 11%, 78% and 67%. Detection rates were especially poor for root cracks. Note that the objective of this project was to identify whether the use of TOFD for rapid search inspection can result in critical defects being missed. The project deliberately concentrated on potential problems in using TOFD as a search technique, and therefore does not provide a global overview of TOFD capability.

In the meantime more comprehensive guidance is needed on the use of TOFD for search scanning and caution should be exercised when using TOFD as a stand alone search method in situations where the results of this project have indicated suspect reliability (e.g. detection of root cracks when there may be mismatch across the weld, detection of cracks in regions where there may be porosity etc.)

References: Silk M.G. and Lidington B.H., Defect Sizing using an Ultrasonic Time Delay Approach, British Journal of NDT, March 1975.