Designation: E2373/E2373M − 14

Standard Practice for Use of the Ultrasonic Time of Flight Diffraction (TOFD) Technique[1]

This standard is issued under the fixed designation E2373/E2373M; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope*

1.1 This practice establishes the requirements for developing ultrasonic examination procedures using the ultrasonic technique known as Time-of-Flight Diffraction (TOFD).

1.2 Consistent with ASTM Policy, TOFD may be regarded as an ultrasonic test method whereby the qualities and characteristics of the item tested are evaluated, measured and in some cases identified. Measurements may be subject to precision and bias that may be determined statistically or as a function of some parameter(s) such as wavelength. This practice may be used for applications that would be qualitative and properly addressed as examinations as well as quantitative and more properly addressed as tests.

1.3 The values stated in either SI units or inch-pound units are to be regarded separately as standard. The values stated in each system may not be exact equivalents; therefore, each system shall be used independently of the other. Combining values from the two systems may result in non-conformance with the standard.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E164 Practice for Contact Ultrasonic Testing of Weldments

E543 Specification for Agencies Performing Nondestructive Testing

E1065 Practice for Evaluating Characteristics of Ultrasonic Search Units

E1316 Terminology for Nondestructive Examinations

E1324 Guide for Measuring Some Electronic Characteristics of Ultrasonic Testing Instruments

E1961 Practice for Mechanized Ultrasonic Testing of Girth Welds Using Zonal Discrimination with Focused Search Units

2.2 *ASNT Documents:*[3]

SNT-TC-1A Recommended Practice for Nondestructive Testing Personnel Qualification and Certification

ANSI/ASNT CP-189 Standard for Qualification and Certification of Nondestructive Testing Personnel

2.3 *Aerospace Industries Association Document:*[4]

NAS-410 Certification and Qualification of Nondestructive Testing Personnel

2.4 *ISO Standard:*[5]

ISO 9712 Non-destructive Testing—Qualification and Certification of NDT Personnel

2.5 *Other Documents:*

Code Case 2235 ASME Boiler and Pressure Vessel Code[6]

EN 583-6 Non-destructive Testing: Ultrasonic Examination. Time-of-flight Diffraction Technique as a Method for Detection and Sizing of Discontinuities

3. Terminology

3.1 *Definitions*—Related terminology is defined in Terminology E1316.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *B-scan display*—a sectional view of the plotted inspection data formed by the stacking of A-scans. (Some users refer to stacked A-scans from non-parallel scans as D-scans and reserve those used with parallel scans as B-scans.)

3.2.2 *back-wall echo*—a specular reflection from the back-wall of the component being examined (usually assumed to be a plate).

[1] This practice is under the jurisdiction of ASTM Committee E07 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.06 on Ultrasonic Method.

Current edition approved June 1, 2014. Published June 2014. Originally approved in 2004. Last previous edition approved in 2009 as E2373 - 09. DOI: 10.1520/E2373_E2373M-14.

[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Ln., Columbus, OH 43228-0518, http://www.asnt.org.

[4] Available from Aerospace Industries Association of America, Inc. (AIA), 1000 Wilson Blvd., Suite 1700, Arlington, VA 22209-3928, http://www.aia-aerospace.org.

[5] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, http://www.iso.org.

[6] Available from the American Society of Mechanical Engineers, ASME International, 22 Law Drive, Box 2900, Fairfield, NJ 07007-2900.

***A Summary of Changes section appears at the end of this standard**

3.2.3 *lateral wave*—a compression wave that travels by the most direct route from the transmitting probe to the receiving probe in a TOFD configuration.

3.2.4 *parallel scan*—a scan whereby the probe pair motion is parallel to the ultrasonic beam axis. Also called a B-scan by some users.

3.2.5 *PCS*—abbreviation for probe center spacing. Refers to the distance between the marked exit points of a pair of TOFD probes for a specific application.

3.2.6 *non-parallel or longitudinal scan*—a scan whereby the probe pair motion is perpendicular to the ultrasonic beam axis.

3.2.7 *RF waveforms*—the non-rectified A-scan.

4. Significance and Use

4.1 This practice provides general principles for the application of the Time-of-Flight Diffraction Technique as a tool for detection and sizing of discontinuities.

4.2 TOFD is a nondestructive ultrasonic examination technique that is not based on amplitude response. However, sufficient sensitivity is required to identify indications for evaluation.

4.3 Techniques used are typically applied to welded joints in carbon steel but the principles may be applicable to other applications including other materials with suitable validation procedures agreeable to the contracting parties.

4.4 In addition to a stand-alone ultrasonic detection technique TOFD may be used in conjunction with weld examinations such as those described in Practices E164 and E1961 where it may be used to improve sizing estimates of flaws detected by the manual or mechanized pulse-echo techniques and help discriminate between flaws and geometric reflectors.

4.5 The technique has proven effective on thicknesses from 9 to 300 mm [0.375 to 12 in.]. TOFD has been used on thicknesses outside of this range but special considerations are necessary. Techniques developed outside of this range of thickness shall be demonstrated as capable of meeting the required detection and sizing requirements of the specification used.

5. Basis of Application

5.1 The following items are subject to contractual agreement between the parties using or referencing this standard.

5.2 *Personnel Qualification*

5.2.1 If specified in the contractual agreement, personnel performing examinations to this standard shall be qualified in accordance with a nationally or internationally recognized NDT personnel qualification practice or standard such as ANSI/ASNT-CP-189, SNT-TC-1A, ISO 9712, NAS-410, or a similar document and certified by the employer or certifying agency, as applicable. The practice or standard used and its applicable revision shall be identified in the contractual agreement between the using parties.

5.3 *Qualification of Nondestructive Agencies*—If specified in the contractual agreement, NDT agencies shall be qualified and evaluated as described in E543. The applicable edition of E543 shall be specified in the contractual agreement.

5.4 *Procedures and Techniques*—The procedures and techniques to be used shall be as specified in the contractual agreement.

5.5 *Surface Preparation*—The pre-examination surface preparation criteria shall be in accordance with 6.3 unless otherwise specified.

5.6 *Timing of Examination*—The timing of examination shall be in accordance with 6.3 unless otherwise specified.

5.7 *Extent of Examination*—The extent of examination shall be in accordance with 6.3 unless otherwise specified.

5.8 *Reporting Criteria/Acceptance Criteria*—Reporting criteria for the examination results shall be in accordance with Section 8 unless otherwise specified. Since acceptance criteria (for example, for reference radiographs) are not specified in this practice, they shall be specified in the contractual agreement.

5.9 *Re-examination of Repaired/Reworked Items*—Reexamination of repaired/reworked items is not addressed in this standard and if required shall be specified in the contractual agreement.

6. Procedures

6.1 *Introduction:*

6.1.1 TOFD is an ultrasonic examination technique that can provide improved detection and sizing capabilities of discontinuities compared to standard ultrasonic pulse-echo techniques. It uses forward scattered tip diffraction and reflection of transmitted ultrasonic pulses. This document describes the requirements for TOFD equipment and procedures on flat plate surfaces. Guidance for more complex geometries is provided in the Appendix. General guidance on TOFD can also be found in EN 583–6. Acceptance criteria typical and performance demonstration requirements that may be used with TOFD techniques are found in ASME Code Case 2235[7].

6.1.2 Because phase inversions of signals play an important role in the evaluation of TOFD results, all procedures developed using this practice shall require that the equipment presentation use and store RF waveforms.

6.1.3 Whether motorized or manually-operated, probe motion must be encoded for position and probes held in a fixture that maintains correct PCS during scanning. Time based sampling of data collection is not acceptable.

6.1.4 Fig. 1 illustrates the typical probe configuration for a TOFD examination. The figure uses a weld for convenience of references; however, TOFD need not be restricted to just weld examinations.

6.1.5 The lateral wave and back-wall echo signals provide convenient references. For most applications mode converted

[7] Reference to ASME CC2235 is made only as an example of an existing code where the mutually agreed upon acceptance criteria allows TOFD to be applied. This does not suggest that application of ASME CC2235 would be appropriate in all cases. It should be recognized that the high sensitivity of the TOFD technique could result in indications from reflectors in plate materials that meet all plate ultrasonic specification requirements. Such indications should not be considered unacceptable unless they fail to meet the acceptance criteria agreed upon in 8.1.

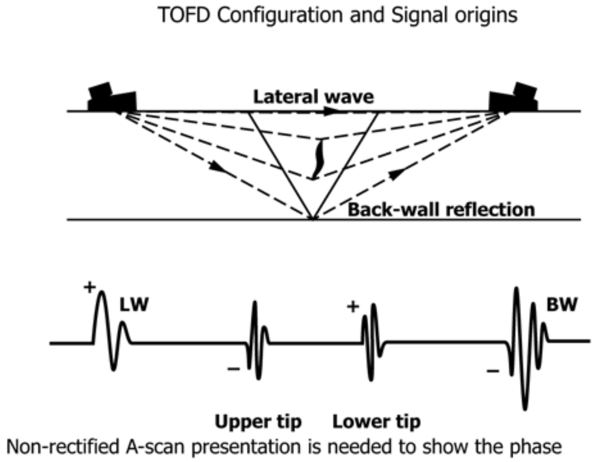


FIG. 1 TOFD Configuration and Signal Origins

signals from flaws are not used and therefore flaw indications are usually recognized as occurring between the lateral wave and back-wall echo signals. Although it is more often the case to use refracted compression mode in the examination piece, some applications may produce better results when the incident angle is greater than the first critical angle, thereby providing a refracted transverse shear mode in the examination piece. When using a refracted compression mode in the examination piece the direct shear and head waves also are generated; however, due to their lower acoustic velocities, shear waves arrive later in time than the back-wall signal.

6.1.6 Fig. 2 is a sketch of a typical presentation for a non-parallel scan of a butt weld in a plate with an imbedded flaw. The right side of Fig. 2 illustrates a waveform extracted from a B-scan display showing the lateral wave, upper tip diffracted, lower tip diffracted and the back-wall echo signals. The left side of Fig. 2 indicates the probe placement with respect to the weld (upper left) and relative motion of the probes (a non-parallel scan is indicated).

6.1.7 Fig. 3 illustrates an actual TOFD scan with five indications (identified on the left) and an extracted A-scan from one of the indications.

6.2 *Written Procedure*—A documented examination strategy or scan plan shall be provided showing probe placement, movement, and component coverage that provides a standardized and repeatable methodology for component acceptance. The scan plan shall also include ultrasonic beam angle(s) used, beam directions with respect to some reference such as a weld centerline, and volume examined.

6.3 *Examination Materials and Surface Preparation:*

6.3.1 TOFD technique can be applied to both metals and nonmetals. Best results are had on fine-grained isotropic materials with low attenuation including some finer grained austenitic alloys and aluminum. With suitable validation procedures, agreeable to the contracting parties, coarser-grained and anisotropic materials may also be examined using TOFD. These usually require additional modifications to frequencies and digital signal processing.

6.3.2 The scanning area shall be clear of weld spatter and other conditions which may interfere with the movement of the probes, the coupling liquid, or the transmission of acoustic energy into the material. Any surface condition such as geometry, coating, and so forth, impeding the ultrasonic examination shall be noted for corrective action prior to scanning.

6.3.3 The TOFD technique may be used with immersion, contact or gap techniques. Single element or phased array piezoelectric probes may be used. EMAT or other non-standard probes may also be used with suitable validation procedures agreeable to the contracting parties.

6.3.4 The acoustic coupling shall be obtained by using a medium suitable for the purpose and compatible with the material being examined. Water, coupling gels or pastes, greases and oils are typically used. Water additives such as environmentally-safe wetting agent and corrosion inhibitors

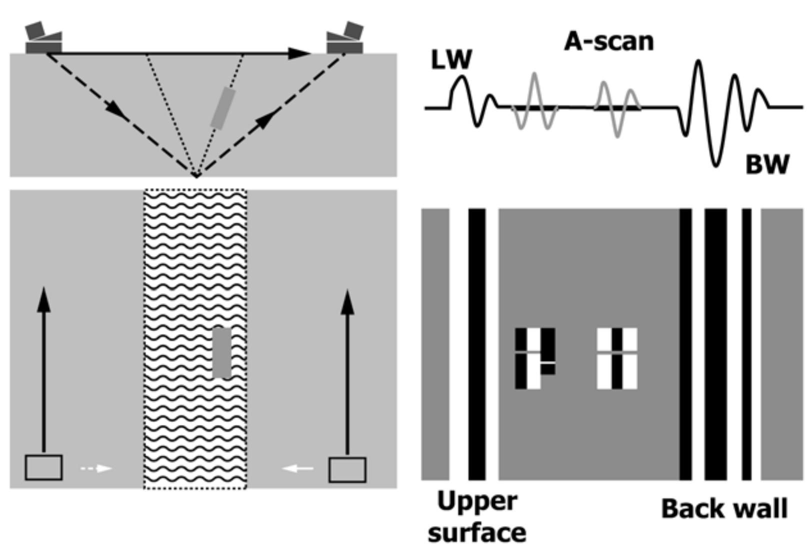


FIG. 2 Schematic Representation of TOFD Scan (Left) and Data Display (Right)

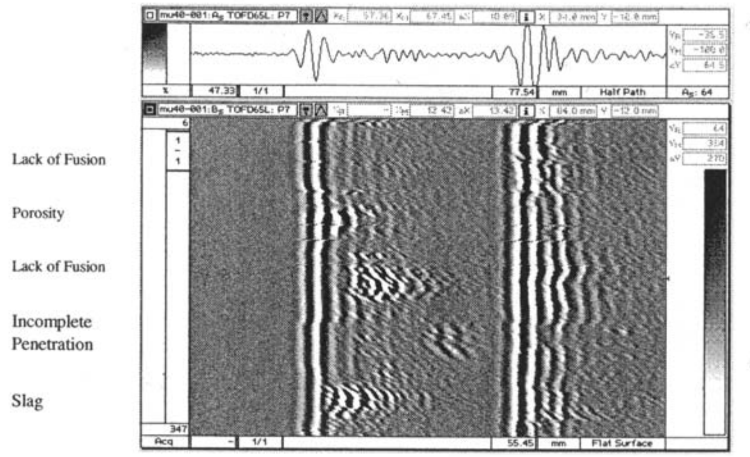


FIG. 3 Sample Display (Real Data) of a Nonparallel Scan of a Weld with Flaws Identified

may be used to enhance acoustic coupling and protect the examination piece. For examination where ambient temperatures are below 0°C [32°F] methyl alcohol or similar media may be used. For examination at elevated temperatures the examination surface or probes may require cool-down or specially designed high-temperature couplants. The coupling medium selected shall provide uniform and reliable examination in the temperature range of intended use. Couplant and scanning conditions, including temperature, used for standardization shall be the same as that used in the examination.

6.3.5 Examination should occur after welding when the surface temperature is cooled to less than 40°C [100°F]. Surface preparation shall be adequate to provide surface access to examine the entire weld volume and heat affected zones.

6.4 *Qualification and Certification of Personnel*—If specified in the contractual agreement, personnel performing examinations to this practice shall be qualified in accordance with a nationally-recognized NDT personnel qualification standard and certified by the employer or certifying agency as applicable. The practice or standard used and its applicable version shall be identified in the contractual agreement between the using parties and should include a requirement for training specific to TOFD.

6.5 *Equipment Requirements*—An ultrasonic system for TOFD shall provide a means of transmitting, receiving, storing, displaying and analyzing ultrasonic signals. As well, it shall provide a fixed spacing between the transmitting and receiving probes and ensure that probe motion is encoded and its position maintained within prescribed tolerances with respect to a reference position such as the weld centerline.

6.5.1 *Electronics:*

6.5.1.1 The instrument shall provide a linear "A" scan presentation for both setting up scan parameters and for signal analysis. Instrument linearity may be determined in accordance with the procedures detailed in Guide E1324, within six months of the intended end use date. For digital-based instruments alternative calibration methods may be used to verify amplitude and time-base output linearity. A copy of the calibration certificate shall be kept on file by the user of the equipment. Instrument linearity shall be such that the accuracy of indicated amplitude or time is within ±5 % of the actual full-scale amplitude or time.

6.5.1.2 The ultrasonic pulser may provide excitation voltage by tone burst, uni-polar or bi-polar square wave. Pulse width shall be tunable to allow optimization of pulse amplitude and duration.

6.5.1.3 The bandwidth of the ultrasonic receiver shall be at least equal to that of the nominal probe frequency and such that the −6 dB bandwidth of the probe does not fall outside of the −6 dB bandwidth of the receiver.

6.5.1.4 Receiver gain control shall be available to adjust signal amplitude in increments of 1 dB or less. Since diffracted signal amplitudes may be significantly lower than for pulse-echo techniques it may be necessary to incorporate a pre-amplifier in the system.

6.5.1.5 Analogue to digital conversion of waveforms shall have sampling rates at least four times that of the nominal frequency of the probe. When digital signal processing is to be carried out on the raw data this shall be increased to eight times the nominal frequency of the probe.

6.5.2 *Data Display and Recording:*

6.5.2.1 The data display used for TOFD shall allow the operator to view the un-rectified A-scan and position the start and length of a gate that determines the extent of the A-scan time-base that is collected.

6.5.2.2 Data collection equipment shall permit storage of all gated A-scans to a magnetic or optical storage medium. Equipment used for TOFD shall require computer software that provides a B-scan display of the collected waveforms (as illustrated in Fig. 2). The B-scan display shall have a minimum of 64 gray-scale or color levels. (Storage of just B-scan images without the underlying A-scan waveforms is not an acceptable form of data recording.)

6.5.2.3 Computer software for TOFD displays shall include algorithms to linearize cursors or the waveform time-base to permit depth and vertical extent estimations.

6.5.2.4 In addition to storage of waveform data including amplitude and time-base details, the TOFD equipment shall also store positional information indicating the relative position of the waveform with respect to the adjacent waveform(s); that is, encoded position.

6.5.3 *Probes*—Ultrasonic probes used for TOFD techniques shall conform to the following minimum requirements:

6.5.3.1 Two probes shall be used in a pitch-catch arrangement (TOFD pair).

6.5.3.2 Each probe in the TOFD pair shall have the same nominal frequency.

6.5.3.3 The TOFD pair shall have the same element dimensions.

6.5.3.4 The pulse duration of the probe shall not exceed two cycles as measured to the 20 dB level below the peak response (Guide E1065 may be used to evaluate characteristics of probes).

6.5.3.5 Guide E1065, Annex A1 may be used to determine the probe bandwidth. This should be used to assess the receiver bandwidth requirements as stated in 6.5.1.

6.5.3.6 Probes may be focused or unfocused. Unfocused probes are recommended for detection and focused probes are recommended for improved resolution for sizing.

6.5.3.7 Probes may be single element or phased array. EMAT probes may be used with suitable validation procedures agreeable to the contracting parties.

6.5.4 *Mechanics:*

6.5.4.1 Mechanical holders shall be used to ensure that probe spacing is maintained at a fixed distance (typically termed the "probe center spacing" or PCS in other literature). The mechanical holders shall also ensure that alignment to the intended scan axis on the examination piece is maintained to a tolerance agreed upon between contracting parties.

6.5.4.2 Probe motion may be achieved using motorized or manual means but in all cases, the mechanical holder for the probes shall be equipped with a positional encoder that is synchronized with the sampling of A-scans.

6.5.5

6.6 *Apparatus Set-up*—Fig. 4 provides a schematic of the minimum equipment requirements for a TOFD examination.

6.7 *Probe Selection:*

6.7.1 Probe selection shall be based on the application requirements. The following tables provide initial recommended probe parameters for specified thickness ranges in ferritic steels. For austenitic or other attenuative materials, nominal frequencies normally need to be reduced and element sizes increased.

TABLE 1 For Steel Thickness Ranges up to 75 mm [3 in.]

Nominal Wall Thickness mm [in.]	Nominal Frequency (MHz)	Element Size mm [in.]	Recommended Angles
<12 [0.5]	10 to 15	2 to 6 [0.08 to 0.25]	60 to 70°
12 to <35 [0.5 to 1.4]	5 to 10	2 to 6 [0.25 to 0.5]	50 to 70°
35 to <75 [1.4 to 3]	2 to 5	6 to 12 [0.25 to 0.5]	45 to 65°

6.7.2 For thickness ranges in steel 75 to 300 mm, the beam divergence from a single element is not likely to provide sufficient intensity for good detection over the entire thickness. For thickness 75 mm [3 in.] and greater (in steel) the examination piece shall be divided into multiple zones. For thickness 75 mm [3 in.] and greater (in steel) and when required in smaller thickness, sensitivity targets shall be placed in a reference block at least at 25 % and 75 % through thickness in each zone to verify that there is adequate beam coverage for the multiple zone technique used.

TABLE 2 For Multiple Zones in Steel with Thicknesses Up to 300 mm [12 in.]

Nominal Wall mm [in.]	Nominal Frequency (MHz)	Element Size mm [in.]	Recommended Angle
<35 [<1.4]	5 to 15	3 to 6 [0.125 to 0.25]	50 to 70°
≥35 to 300 [≥1.4 to 12]	1 to 5	6 to 12.5 [0.25 to 0.5]	45 to 65°

6.7.3 On thick sections requiring more than one TOFD pair the lateral wave or back-wall signal may not always be visible. Therefore, provision in the linearizing algorithms must be made to permit inputs of other parameters instead of the lateral and back-wall signal positions. For wall thickness less than 75 mm [3 in.], technique qualifications may require they too be divided into smaller ranges with each range addressed by a dedicated TOFD pair.

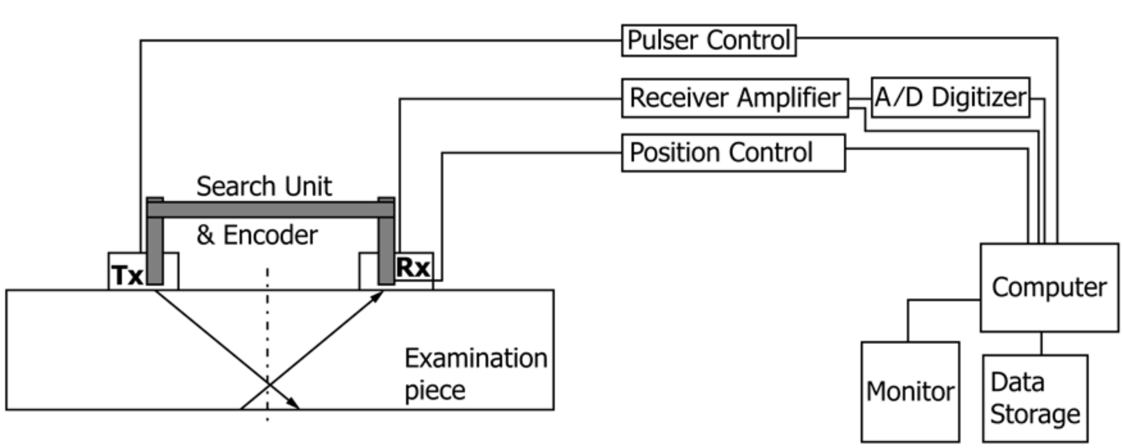


FIG. 4 Schematic of Minimum TOFD Apparatus

6.8 *Sensitivity:*

6.8.1 TOFD is a non-amplitude based detection and sizing technique; however, sufficient sensitivity must be used to ensure flaw indications can be seen on the B-scan display. In most cases where a single TOFD pair is used an adequate sensitivity can be achieved by setting the lateral wave amplitude to 40 to 90 % of the full screen height. Alternatively sensitivity may be established based on a noise level from grain scatter (typically 10-15 % screen height or 6 dB greater than the electrical noise prior to the lateral wave signal) or from the response from reference targets.

6.8.2 Unless alternative sensitivity targets or techniques are agreed upon by the contracting parties, sensitivity shall be assessed using the response from side-drilled holes. Examples of reference block design considerations are shown in Appendix 1. Side-drilled holes should be placed in reference blocks of material having similar acoustic properties to the examination piece and the reference block shall be within ±10 % of the nominal thickness of the piece to be examined for thicknesses up to 100 mm. For thicknesses over 100 mm [4 in.] the reference blocks shall be within ±10 mm [0.4 in]. Where the examination piece is curved the reference block diameter shall be within 0.9 to 1.5 of the diameter of the part to be examined for curvatures under 0.3 m [12 in.]. For curvatures greater than 0.3 m [12 in.] diameter the reference block may be flat. Further considerations to matching the reference block curvature to the examination piece's curvature shall be made when the refracting wedge is machined to match the examination piece's curvature and when the examination directs the beam circumferentially.

6.8.3 A minimum of two side-drilled holes shall be used to establish sensitivity settings and coverage. Table 3 suggests hole diameters for various thicknesses. When only two side-drilled holes are used, placement of the side-drilled holes shall be at 25 % and 75 % of the nominal wall thickness for wall thicknesses less than 75 mm [3 in.]. Where wall thicknesses 75 mm [3 in.] and over are to be examined (as in Table 2), and in thicknesses less than 75 mm [3 in.] when multiple zones are used, side-drilled holes shall be placed at the 25 % and 75 % depths for each zone. Note that for thin sections the lateral wave may not permit the resolution of the target at 25 % wall thickness so the sensitivity may be set using the response from the target at 75 % wall thickness.

6.8.4 When using more than one TOFD pair for thicker sections, multiple channel equipment may be used. If only single channel capability is available, multiple scans may be used with a separate scan for each TOFD pair.

6.8.5 When setting sensitivity by using side drilled holes in the reference block the amplitude response from the weaker of the two reference side-drilled holes shall be set to 80 % full screen height. This shall be considered "reference sensitivity." Scanning level sensitivity in dB above or below this level shall be established between the contracting parties. When multiple zones are used for thicker sections, evidence of the volume coverage should be established by detection of the nearest side-drilled hole from the adjacent zone.

TABLE 3 Suggested Diameters of Side-drilled Holes

Material Thickness mm [in.]	Hole Diameter mm [in.]
<10 [0.375]	1.5 [0.060]
10 to 35 [0.375 to 1.4]	3 [0.125]
>35 [1.4]	6 [0.250]

6.8.6 Sensitivity to weak signals or signals poorly defined in coarse-grained materials may be enhanced using signal averaging or digital signal processing.

6.8.7 Sensitivity to near-surface indications may be enhanced by using; higher-frequency probes, smaller PCS, lateral wave straightening and subtraction algorithms.

6.8.8 Signal enhancement using digital signal processing for straightening and signal subtraction may be used only after the raw data has been collected and stored. Signal averaging may be used during the collection of raw data. Digital signal processing used to enhance detection and sizing capabilities may also be stored but shall not replace the raw data.

6.9 *Scan Width Coverage*—When performing weld examinations using non-parallel scans on narrow gap welds, the depth error due to the diffractor not being at the centerline of the weld will be small. However, for single-V butt welds or double-V butt welds in heavy wall materials the distance that a flaw may occur from the weld centerline can be a significant percentage of the PCS. These conditions may result in depth estimation errors and a lack of information to correctly position the flaw. Where concern exists for these uncertainties the techniques should incorporate options such as multiple non-parallel scans with the PCS offset from the weld centerline, and a requirement for parallel scans wherever relevant flaws are detected or augmenting the TOFD scanning with pulse-echo techniques.

6.10 *Recording of Data:*

6.10.1 Scanning using gap or contact techniques may result in small variations in the arrival times of the lateral wave due to slight surface irregularities or "stuttering" of the probe as it is dragged along the surface. In order to allow for such variations in the arrival time of the lateral wave, the gate used to collect the A-Scan waveforms shall be started a minimum of 0.5 µs prior to lateral wave when setting signal positions in a static mode. The gated region shall be set long enough to see, as a minimum, all of the back-wall signal with allowance for thickness and mismatch variations. Useful data can be had from mode-converted signals therefore the interval from the back-wall to the mode-converted signals from the back-wall may also be included in data collection.

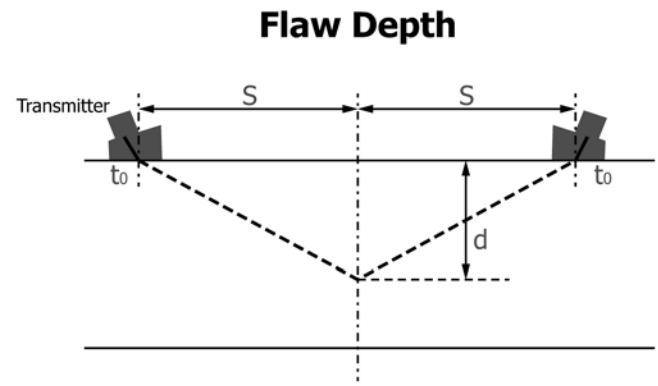
6.10.2 A maximum sample spacing of 1 mm [0.040 in.] shall be used between A-scans collected for thicknesses under 50 mm [2 in.] and a sample spacing of up to 2 mm [0.080 in.] may be used for thicker components.

6.10.3 Scanning speed will be limited by mechanical ability to maintain acoustic coupling and by the system's electronic ability to ensure full waveforms are captured without missing data-points. Missing lines in the B-scan display shall not exceed 5 % of the scan lines to be collected, and no adjacent lines shall be missed.

6.11 *Sizing and Positioning of Indications*—Sizing algorithms for estimating vertical extent by TOFD shall be based on the sound paths and knowledge of critical parameters (PCS, wall thickness, wedge delay, acoustic velocities of examination and coupling materials). The operator shall use phase information from the A-scans extracted from the B-scan to assess flaw vertical height and depth. Position along or across the weld or reference axis shall be determined using the encoded positioning system. When multiple probes are used simultaneously (multiple channel instruments) for examination of thick sections or for improved sizing resolution, any lateral off-sets between probes shall be accommodated on the image reconstruction. This is intended to ensure that indications from the same target can be aligned to the same reference (for example, if a 50 mm [2 in.] separation is needed between two TOFD pairs then one may be reference but the other must be corrected for the 50 mm [2 in.] positional difference when reconstructing the D-scan image on the screen). Assessing the flat portion of an indication's initial arrival time on the B-scan usually improves flaw length determination. Hyperbolic curve fitting algorithms or Synthetic Aperture Focusing Technique (SAFT) may be incorporated into the TOFD analysis software to aid in flaw length determination. Curve fitting is limited to simple rectangular flaws but may underestimate lengths where edges are rounded or slope quickly (see Fig. 5).

6.11.1 *Flaw Depth Determination*—Depth from the examination surface to the upper edge of a flaw is determined from knowledge of the indication arrival time and the set-up parameters. Fig. 6 shows the equation used to determine flaw depth "d." Time "t" is the total time from the transmitter to the receiver of the flaw and "t_0" is the time in the wedge material. Acoustic velocity is indicated by "c" and "S" is half the PCS as measured along the examination surface. This example is applicable to flat-plate calculations only.

6.11.2 *Flaw Height Determination*—To determine flaw height or vertical extent the same equation is used for the lower tip signal. This provides two depths. The lesser depth subtracted from the greater provides the flaw height. This is shown in Fig. 7. This example is applicable to flat-plate calculations only.



$$d = \sqrt{\left(\frac{c}{2}\right)^2 \bullet (t - 2t_0)^2 - S^2}$$

FIG. 6 Depth to Flaw Determination

NOTE 1—The time of arrival of the upper and lower tip signals must use the appropriate phase relative to the lateral wave as indicated in Fig. 1.

6.12 *Limitations of the Technique:*

6.12.1 Due to the presence of the lateral wave and back-wall echo signals, flaws occurring in these "dead zones" may not be detected. Geometric conditions such as mismatch or plate curvature can exacerbate these dead-zone conditions.

6.12.2 Even if a flaw is detected near one of the dead zones, sizing ability may be limited if the upper or lower tip signal cannot be separated from the lateral or back-wall signals

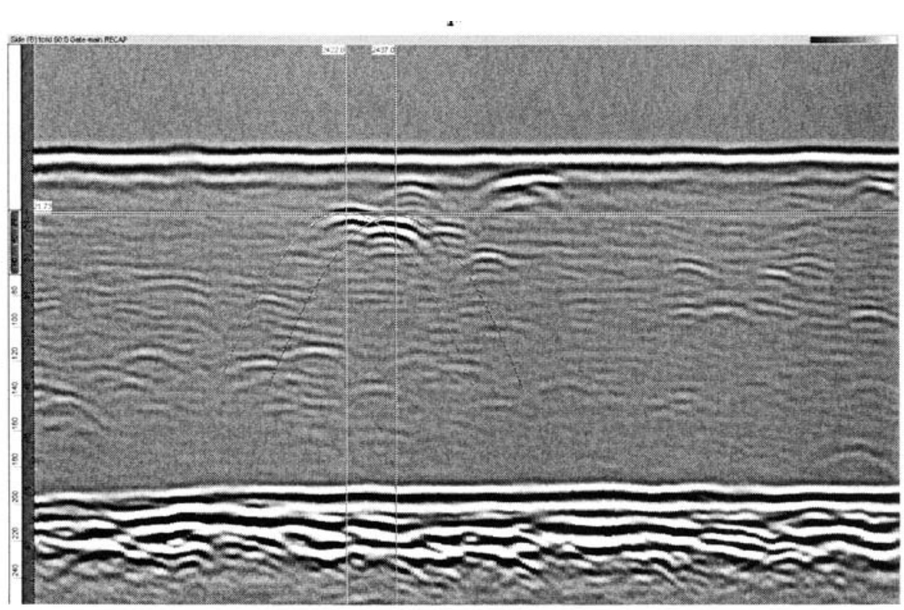


FIG. 5 Image of Curve Fitting for Length Determination

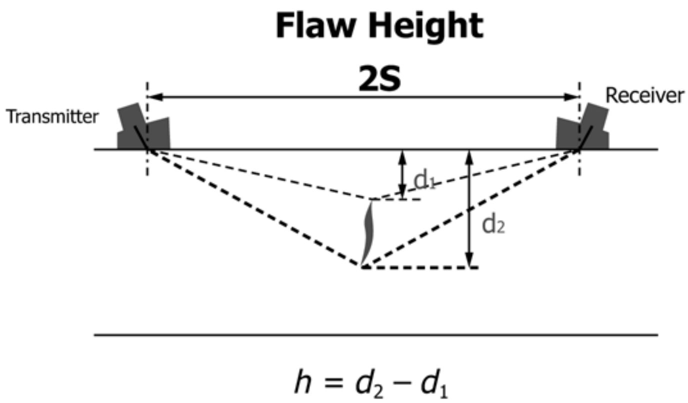


FIG. 7 Flaw Height Determination

respectively. In some cases small subsurface flaws near the back-wall will not be possible to discriminate from surface-connected flaws.

6.12.3 Midwall flaws, especially those in the lower half of the wall thickness have the best chance of being assessed for vertical extent by TOFD. However, in order for this assessment the flaw must have a vertical extent that is significantly greater than the equivalent time of the upper tip-diffracted pulse so that the upper and lower tip-diffracted signals can be seen separately ensuring that the correct phase portions are used for sizing. In other words, the top and bottom signals should be clearly separated.

6.12.4 Further scanning may be performed using different probes (focused, higher frequency, higher damping, lower angles, and so forth) as well as scanning from the opposite surface, to try to overcome some of these limitations.

7. TOFD Analysis

7.1 *Quality:*

7.1.1 TOFD images shall be assessed for quality of data collected prior to analysis of data. Image assessment shall be based on:

7.1.1.1 Amplitude of laterals wave being between 40 to 90 % for single zone techniques or verification of sensitivity with respect to reference sensitivity as verified in intervals of not greater than 4 h.

7.1.1.2 Missing data lines being within allowed parameters defined in 6.10.

7.1.1.3 Adequate overlap (for example, a length of weld scanned as three separate acquisition scans or a girth weld where the stop position is made past the start position). Minimum overlap shall be 25 mm [1 in.].

7.1.1.4 Adequate coupling flow as evidenced by no loss of signal amplitude (lateral wave, back wall signal or grain noise may be observed to ensure amplitude drop is not greater than 6 dB).

7.1.2 Scans with unacceptable quality shall be redone with deficiencies corrected.

7.2 *Relevant Indications:*

7.2.1 Relevant indications may be classified as either surface or embedded.

7.2.2 Embedded flaw indications can be further classified as:

7.2.2.1 Point-like (having no measurable length),

7.2.2.2 Elongated threadlike (having no measurable height), and

7.2.2.3 Elongated with height (having a measurable height).

7.2.3 Surface flaws may be identified by the surface on which they occur; scanning surface, far surface or through wall. Through wall surface flaws have both surfaces affected as evidenced by a reduction or elimination of the lateral and back wall signals accompanied by diffracted signals from both ends.

7.3 *Tolerances:*

7.3.1 The degree to which the position of an indication in a TOFD scan can accurately be defined is the precision of the system. This will depend on the equipment used, the geometry of the part tested and the accuracy of the timing of received signals. When precision tolerance is required the contracting parties should agree upon the methods used to define the tolerance. For example, this may use a summation of uncertainties, a statistical analysis of uncertainties or some form of statistical analysis of positioning and sizing errors compared to destructive testing on qualification samples. For a detailed description of uncertainties EN 583–6 may be used.

8. Reporting and Acceptance Criteria

8.1 Details of reporting results and acceptance criteria shall be agreed upon by the contracting parties.

8.2 Where flaw aspect ratio is used as part of the acceptance criteria, a policy for length and height assessment shall be established between the contracting parties. Where indications do not allow a clearly defined upper and lower tip diffracted signal to be discerned, a minimum vertical extent may be used based on the ring time of the indication. Where upper and lower tip signals cannot be observed rescans may be recommended using higher frequency and higher bandwidth probes, focused probes, different angles and parallel scans to optimize signal responses.

8.3 As a minimum the report shall include the following:

8.3.1 Part description (including thickness, geometry and material),

8.3.2 Date of examination,

8.3.3 Name of operator,

8.3.4 Name of data storage files and a description of their contents,

8.3.5 A sketch of the scan on the part showing the reference point and scan direction,

8.3.6 Surface conditions and temperature (if outside 0 to 40°C),

8.3.7 Ultrasonic and scanning equipment used,

8.3.8 Reference block details,

8.3.9 Couplant details,

8.3.10 Sensitivity level and range settings,

8.3.11 Scan resolution and digitizing frequency,

8.3.12 Scanning restrictions, and

8.3.13 Status of the examination (accept or reject in accordance with the acceptance criteria stipulated including location, size, and classification of any relevant indications).

8.4 Additionally, when required by contracting parties, files containing raw data pertinent to the results shall be put onto a suitable storage medium and presented as part of the report. Arrangements may be made for a viewer software to be made available.

8.5 A hardcopy of the scan results need not be presented unless required by agreement between the contracting parties. Contracting parties shall decide if a hardcopy of all scanning results is required or if only areas identified as containing relevant flaw indications should be included on hardcopies.

9. Keywords

9.1 flaw-height sizing; flaw sizing; nondestructive testing; time-of-flight-diffraction; TOFD; ultrasonic

APPENDIXES

(Nonmandatory Information)

X1. SAMPLE REFERENCE SENSITIVITY BLOCKS

X1.1 *For Steel Thickness Ranges up to 75 mm [3 in.]*:

X1.1.1 TOFD examinations on thickness ranges up to 75 mm [3 in.] may be done using a single reference block. Fig. X1.1 illustrates how such a reference block may be designed.

NOTE X1.1—In addition to the side-drilled hole locations in the reference block, Fig. X1.1 illustrates a typical probe placement for initial detection scanning for a TOFD technique. Rays indicating the center of beam axes for the transmitting and receiving probes are usually set to cross at a depth of approximately ⅔ thickness. An included angle of about 110 to 120° at the ⅔ thickness is recommended as an initial starting point. But other factors including examination piece geometry and specific area(s) of interest within the volume may result in other or extra probes, probe angles or probe separations being used as well as the need for multiple zone techniques or additional off-set or parallel scans.

X1.1.2 The reference block must have sufficient dimensions to allow the probes to be moved over the examination surface in the direction to be scanned on the examination piece. For the example shown in Fig. X1.1 the longitudinal scan (that is, parallel to the long axes of the side-drilled holes) would require sufficient depth into the plane of the page to permit the scanning fixture and the encoder to advance sufficiently to collect at least 25 to 30 mm [1 to 1.25 in.] of sample distance. If a parallel scan was to be performed on the reference block in Fig. X1.1 the block dimension in the plane of the page would need to be approximately 2 PCS lengths.

X1.2 *For Steel Thickness Ranges from 75 mm [3 in.] to 300 mm [12 in.]*:

X1.2.1 As noted in 6.7, thick sections examined by TOFD require that the examination piece be divided into multiple zones. Sensitivity targets are placed at 25 % and 75 % through thickness in each zone to verify that there is adequate beam coverage for the multiple zone technique used. Fig. X1.2 illustrates typically suggested hole and probe placement for a wall thickness requiring more than one TOFD pair to ensure full coverage. Hole placement is based on a wall thickness sufficient to require that the section be divided into two zones. Each section is then provided with a side-drilled hole at 25 % and 75 % wall thickness of the zone thickness. Table X1.1 suggests zones for wall thickness up to 300 mm [12 in.].

TABLE X1.1 Suggested Zones for Wall Thicknesses Up to 300 mm [12 in.]

Thickness (t) mm [in.]	Number of TOFD Zones	Depth Range	Beam Intersection (approx.)
<50 [<2]	1	0 to t	2/3 t
50 to 100 [≥2 to <4]	2	0 to 1/2 1/2 to t	2/3 t 5/6 t
≥100 to <200 [≥4 to <8]	3	0 to 1/3 1/3 to 2/3 2/3 to t	2/9 5/9 8/9
≥200 to <300 [≥8 to <12]	4	0 to 1/4 1/4 to 1/2 1/2 to 3/4 3/4 to t	1/12 5/12 8/12 11/12

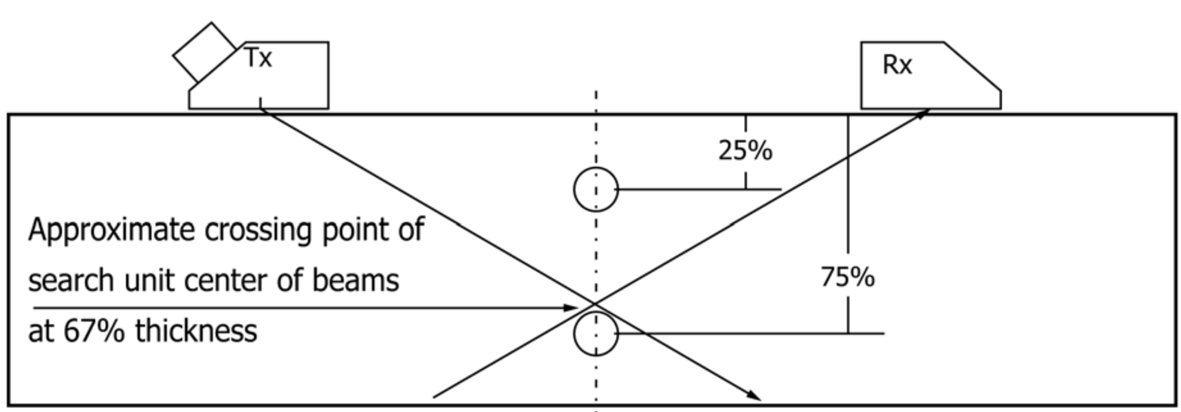


FIG. X1.1 Reference Block for Single TOFD Pair

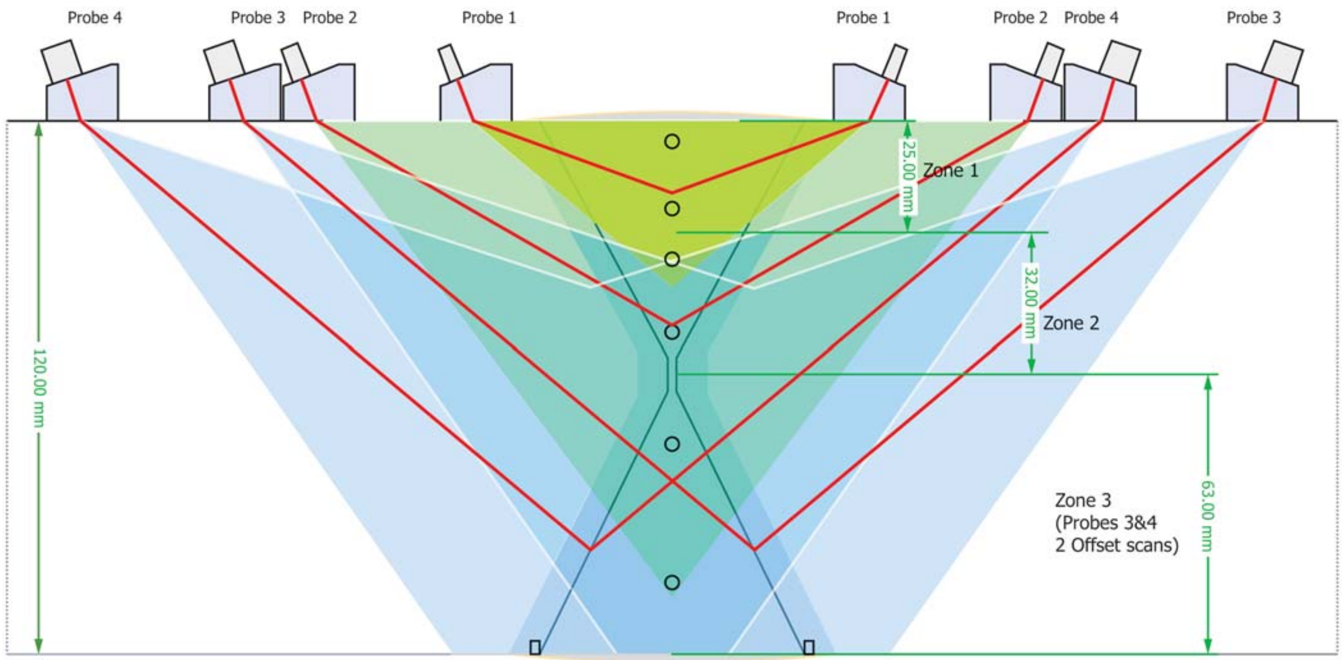


FIG. X1.2 Reference Block for Multiple TOFD Pair

X1.2.2 Although convenient to do so, zones in thick sections need not be equal. Fig. X1.2 also illustrates how an offset scan is required in the lowest zone to address the wide heat affected zone (HAZ). Notches placed at the edges of the HAZ can be used to confirm the coverage required out to the HAZ.

NOTE X1.2—The actual placement of targets is not too critical but this technique will allow some similarities with pulse-echo requirements using side-drilled holes and a method that ensures a uniform and repeatable sensitivity setting. The artificial reflectors used should provide a method of verification of energy distribution in the specimen, a means of reproducing examination sensitivities and a method of demonstrating examination resolution.

X1.3 *Other Targets and Block Configurations*:

X1.3.1 Requirements to assess parameters such as scan surface or opposite surface resolution, phase of flaw indications, volume coverage of beam from a weld centerline, effect of flaw size on detection, and so forth, may not be adequately addressed using just two side drilled hole targets. Other block designs may be used to help determine parameters of concern. Examples of other designs are provided here.

X1.3.2 Fig. X1.3 shows a representation of five flat-bottom holes arranged in a line. The holes should be the same diameter, typically 1.5 to 3 mm [0.6 to 0.12 in.] and drilled to varying depths. Varying depths allows assessment of energy distribution and, resolution capabilities. Surface resolution for indications surface breaking or near-surface indications may be assessed by placement of the maximum and minimum hole-depths. This arrangement of targets allows for assessment of sensitivity to offset from the centerline. By performing several non-parallel scans each with increasing distance of the PCS midpoint from the line connecting the holes, the limits of sensitivity to off-axis can be determined. This may be useful when determining if multiple off-set scans are required to ensure coverage of wide areas such as welds with wide heat

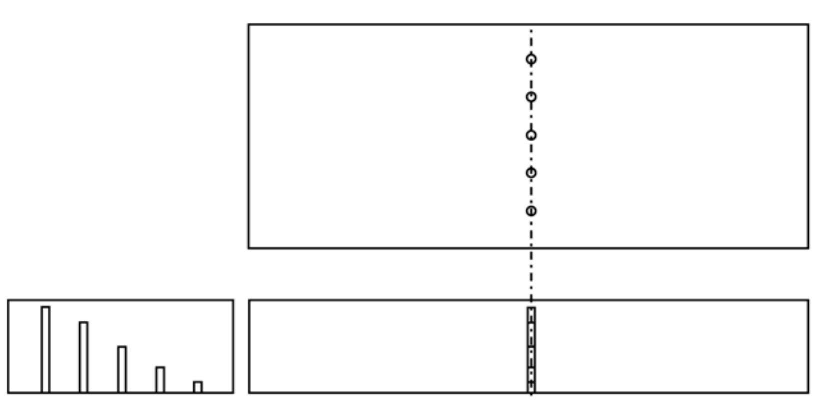


FIG. X1.3 Reference Block Using Flat-bottom Holes

affected zones. The block may also be scanned from the machined surface and the lower tip signals used.

X1.3.3 Fig. X1.4 shows a block with a similar layout to that in Fig. X1.3 but instead of flat-bottom holes diffractor notches are used. Notch width would be typically 2 to 5 mm [0.08 to 0.2 in.] and 10 to 20 mm [0.4 to 0.8 in.] long. These are made using electro-discharge machining (EDM). Sensitivity may be set using the diffracted signals from the Vee-notch tips. This configuration of target more accurately indicates the diffracted signals that might be associated with elongated flaws.

X1.3.4 Fig. X1.5 indicates a block that can be used to establish sensitivity and resolution capabilities. Side-drilled holes 3 mm [0.12 in.] diameter would be placed at quarter, half and three-quarter thickness depths. A2 mm [0.08 in.] side-drilled hole is placed so that the upper portion is 3 mm [0.12 in.] below the scan surface. A notch typically 1 to 2 mm [0.04 to 0.08 in.] high and 10 to 20 mm [0.4 to 0.8 in.] long can be used to assess opposite surface resolution. The notch should be as narrow as is reasonably possible; that is, less than 1 mm [0.04 in.]. Overall block dimensions shall be adequate to ensure that the probes are fully on the block when the PCS is correctly set for the application. The step difference between the side-drilled holes should be adequate to allow independent signals from subsequent holes and increasing depths.

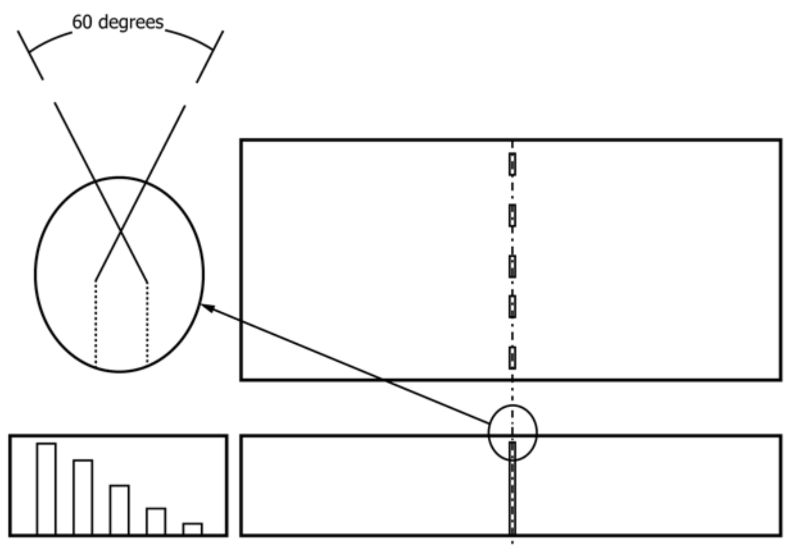


FIG. X1.4 Reference Block Using Tip Diffractors

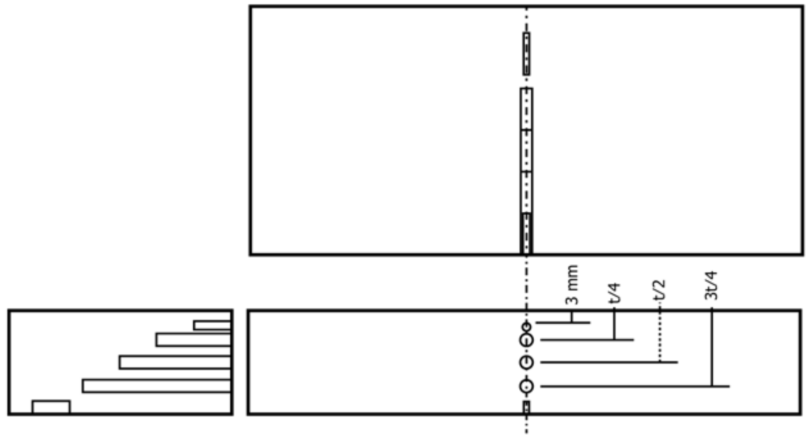


FIG. X1.5 Reference Block Using Stepped and Different Diameter Side-Drilled Holes and Notch

X2. CURVED PLATE

X2.1 This Appendix provides examples of TOFD configurations for examinations of curved plate. Equipment and recording requirements for such configurations must meet the requirements set out in this practice. However, for examination of components other than flat plate, detection and coverage must be qualified to the satisfaction of the contracting parties. Principles described above for flat plate TOFD configurations can be used for examination of other geometries. However, sizing and interpretation of results may be more difficult. Phase inversion considerations may play a part in the way signals are assessed for sizing and depth estimates.

X2.2 *Scanning from a Concave Surface*—This configuration introduces the concept of the lateral wave as a creeping wave (see Fig. X2.1). This applies for the condition where the refracted beam is in compression mode.

X2.3 *Scanning from a Convex Surface*—This configurations introduces the lateral wave as a combined compression and creeping wave due to the potential for a direct and a surface "creeping" path along the examination surface (when the refracted mode is compression). See Fig. X2.2.

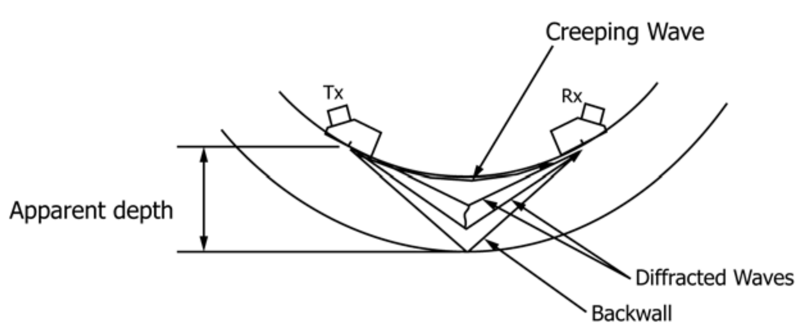


FIG. X2.1 TOFD Pair Placement for Examination from Concave Surfaces

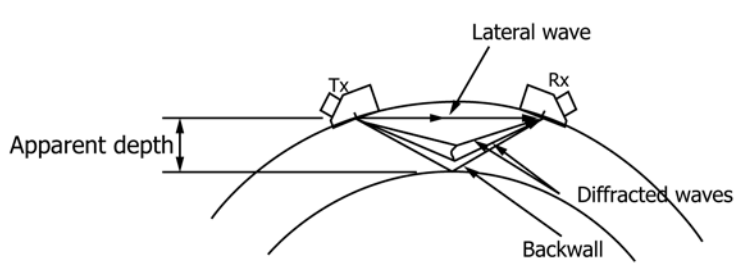


FIG. X2.2 TOFD Pair Placement for Examination from Convex Surfaces

SUMMARY OF CHANGES

Committee E07 has identified the location of selected changes to this standard since the last issue (E2373-09) that may impact the use of this standard.

(1) Standard changed to dual designation, with SI and inch-pound units systems as separately standard.
(2) Added Practice E1961 to Section 2.
(3) Deleted reference to BS 7706 (no longer published) and added its replacement, reference EN 583-6 to Section 2.
(4) Added reference to ISO 9712 to Section 2 and 5.2.1.
(5) Added Summary of Changes section.