

Guide to

**Calibration and setting-up of
the ultrasonic time of flight
diffraction (TOFD) technique
for the detection, location and
sizing of flaws**

UDC 620.179.16.05:53.089.6

Committees responsible for this British Standard

The preparation of this British Standard was entrusted by the Welding Standards Policy Committee (WEE/-) to Technical Committee WEE/46, upon which the following bodies were represented:

Aluminium Federation
 Associated Offices Technical Committee
 Association of Consulting Engineers
 BNF (Fulmer Materials Centre)
 British Airways
 British Chemical Engineering Contractors' Association
 British Coal Corporation
 British Institute of Non-destructive Testing
 British Non-Ferrous Metals Federation
 British Railways Board
 British Steel Industry
 Department of Trade and Industry (Namas Executive)
 Electricity Association
 Health and Safety Executive
 Institute of Physics
 Institute of Quality Assurance
 Light Metal Founders' Association
 Lloyds Register of Shipping
 Ministry of Defence
 National Radiological Protection Board
 Power Generation Contractors' Association (BEAMA Ltd.)
 Railway Industry Association of Great Britain
 Royal Society of Chemistry
 Society of British Aerospace Companies Limited
 Society of Motor Manufacturers and Traders Limited
 Steel Casting Research and Trade Association
 Welding Institute

This British Standard, having been prepared under the direction of the Welding Standards Policy Committee, was published under the authority of the Standards Board and comes into effect on 15 December 1993

© BSI 1993

The following BSI references relate to the work on this standard:
 Committee reference WEE/46
 Draft for comment 92/81577 DC

ISBN 0 580 22311 6

Amendments issued since publication

Amd. No.	Date	Text affected

Contents

	Page
Committees responsible	Inside front cover
Foreword	2
Guide	
1 Scope	3
2 References	4
3 Definitions	4
4 Principles of the method	5
5 Equipment	8
6 Setting-up procedures for flaw detection	10
7 Interpretation of the data	17
8 Estimation of flaw dimensions after flaw detection	19
9 Setting-up procedures for accurate flaw sizing	20
10 Confirmatory measurements	22
11 Accuracy of measurement	22
12 Training and qualification	24
Annexes	
A (informative) Special techniques based on TOFD	25
B (informative) Application of TOFD and reporting criteria	25
C (informative) Suggested steps towards the characterization of flaw echoes in TOFD	27
D (informative) Examples of typical scans	33
E (informative) Suggested framework for training and qualification	35
Figures	
1 D-scan (probe movement normal to beam)	3
2 B-scan (probe movement in direction of beam)	3
3 Diffraction from a crack-like flaw	6
4 Typical pattern of pulses from an internal flaw	7
5 Generalized two probe testing geometry	8
6 Calibration block for TOFD using V notch or electrodischarge machined slit	14
7 Gain setting using grain noise	16
List of references	Inside back cover

Foreword

This British Standard has been prepared under the direction of the Welding Standards Policy Committee. It supersedes DD 174 : 1988, which is withdrawn.

This revision incorporates updated guidance which has resulted from the increased application of the ultrasonic time of flight diffraction technique (TOFD) in industry. The TOFD technique was originally developed at the National Non-destructive Testing Centre at Harwell and has since seen application in a variety of industries. The primary objective of this British Standard is to facilitate the wide implementation of this relatively new non-destructive testing technology in industry. It is envisaged that this British Standard will in due course be superseded by standards that will detail the methods for TOFD technique examination for specific applications.

This British Standard 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.

It is most important to bear in mind that echo amplitude is not used quantitatively by this technique for the determination of flaw size. The conventional amplitude-based flaw sizing associated with ultrasonics is thus largely invalid when this technique is used although it may be used for further discrimination.

The echo amplitude is only employed in TOFD measurements in connection with three tasks.

- (a) Where the pulses from the flaws being sought have to be resolvable against the local noise background, for instance the ultrasonic grain scatter. To ensure that this is the case (or to place limits on the validity of a particular measurement) the known or experimentally determined variation of pulse amplitude as a function of range, position in the ultrasonic beam, etc. may be invoked.
- (b) Where the relative amplitudes of echoes from the top and bottom extremities of flaws may provide important clues about the character of the flaw.
- (c) Where the amplitude of the pulse from an artificial flaw can be used to confirm that system calibration has not changed during a measurement or from measurement to measurement.

The use of TOFD should be considered in any inspection task requiring rapid and reliable flaw detection coupled with an accurate assessment of flaw size. It can be adapted to many test geometries with little difficulty but special instructions and equipment may be needed for the inspection of complex geometries such as nodes or nozzles. Care should also be taken if the technique is considered for use on coarse-grained or ultrasonically difficult materials.

It is recognized that equipment suitable for carrying out the TOFD technique is not yet widely available and this British Standard, which is written in sufficiently general terms to be applicable to the types of equipment currently known to be employed for TOFD, describes the nature of the equipment required and also its calibration.

It is assumed in the drafting of this British Standard that the execution of its provisions is entrusted to appropriately qualified and experienced non-destructive testing personnel.

Compliance with a British Standard does not of itself confer immunity from legal obligations.

Guide

1 Scope

This British Standard provides guidance for the calibration and setting-up of equipment for the use of the two probe version of TOFD both to locate and size flaws as a result of D-scanning (see figure 1) and to size flaws using linear and B-scanning (see figure 2).

The linear scan will cover many testpiece geometries of importance including butt welds in tubes, vessels and plates.

In clauses 4 to 7 of this British Standard it is assumed that only a simple D-scan is to be carried out; for example following the line of a weld. The data required to recognize and initially size potential flaws is thus obtained as a result of this single scan. This means that the potential accuracy of the technique will not be fully achieved.

For critical flaws, it is advisable to utilize TOFD in its most accurate sizing mode as a secondary technique. This involves the linear scan of the transducer pair across the flaw, perpendicular to the flaw's length direction, a process known as B-scanning. Clauses 8 to 11 of this British Standard describe this more accurate TOFD sizing approach in greater detail.

The manner in which the nature of the echoes observed may be used to provide a preliminary and conservative classification of flaws is described in clause 7. Where there are difficulties in interpretation, further transverse TOFD scans or pulse echo measurements may resolve ambiguities. Brief descriptions of special techniques based on TOFD which may be of use in particular inspections are given in annex A. Guidance on the application of TOFD and the reporting criteria is given in annex B.

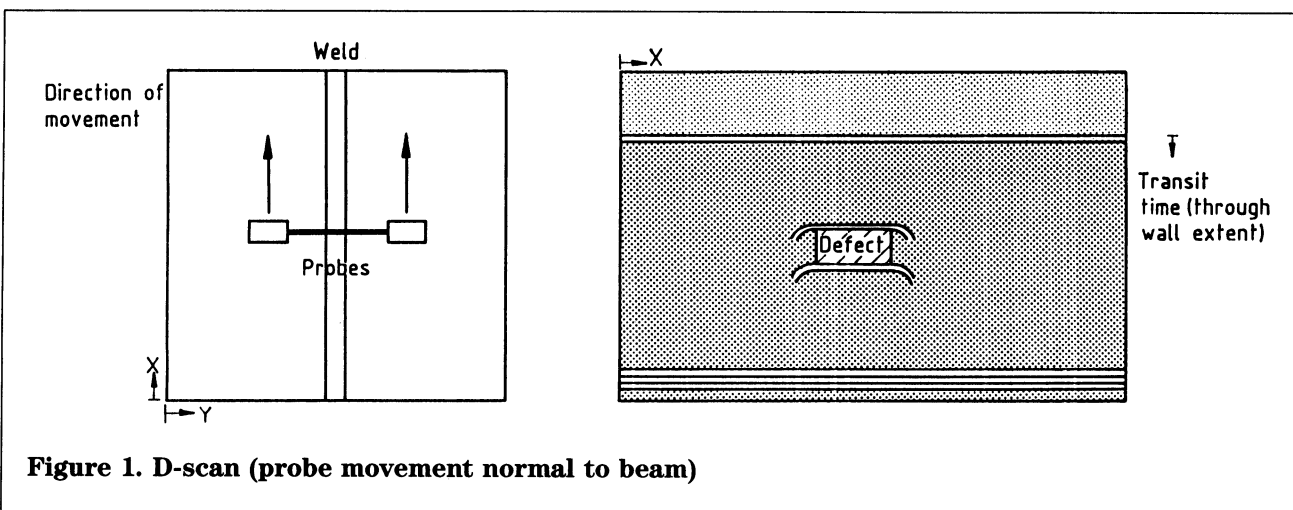


Figure 1. D-scan (probe movement normal to beam)

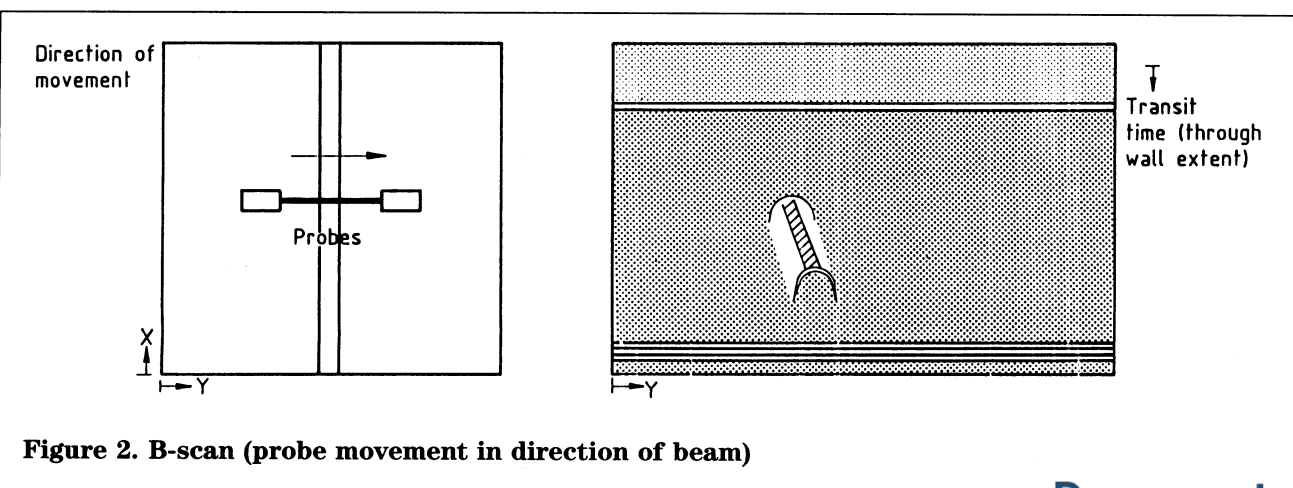


Figure 2. B-scan (probe movement in direction of beam)

2 References

2.1 Normative references

This British Standard incorporates, by reference, provisions from specific editions of other publications. These normative references are cited at the appropriate points in the text and the publications are listed on the inside back cover. Subsequent amendments to, or revisions of, any of these publications apply to this British Standard only when incorporated in it by updating or revision.

2.2 Informative references

This British Standard refers to other publications that provide information or guidance. Editions of these publications current at the time of issue of this standard are listed on the inside back cover, but reference should be made to the latest editions.

3 Definitions

For the purposes of this British Standard the definitions given in BS 3683 : Part 4 : 1985 apply, together with the following which are specific to the TOFD technique.

3.1 scanned surface

Surface on which the probes are placed or, in immersion testing, the surface through which the ultrasonic energy enters the specimen.

3.2 far surface

Opposite surface to the scanned surface.

3.3 flaw depth

Distance of the upper extremity of the flaw below the scanned surface.

3.4 flaw height

Distance between the upper and lower extremities of a flaw projected on to a through thickness plane.

3.5 D-scan

Scan that shows the data collected when scanning the probe pair normal to the direction of the beam along a weld or flaw. The D-scan is the usual representation at the flaw detection stage (see figure 1).

NOTE 1. This nomenclature has been used in this document but it should be noted that in the literature to date this distinction between B-scans and D-scans has not always been made in reporting TOFD data.

NOTE 2. These are also known as linear, non-parallel or longitudinal scans.

3.6 B-scan

Scan that shows the data collected when scanning the probe pair in the direction of the beam transversely across a weld or flaw (see figure 2).

NOTE 1. The B-scan may be used for more accurate location and sizing following the defect detection stage.

NOTE 2. These are also known as transverse, parallel or lateral scans.

3.7 upper flaw extremity

Flaw extremity or tip nearest the scanned surface.

3.8 lower flaw extremity

Flaw extremity or tip farthest from the scanned surface.

3.9 lateral wave

Wave that runs directly between two TOFD probes on a flat or convex surface.

3.10 creeping wave

Wave that runs between two TOFD probes on a flat or concave surface.

NOTE. The flat surface is an intermediate case and either lateral wave or creeping wave may be used.

3.11 back wall echo

Echo due to the wave reflected from the rear surface.

3.12 polarization

Shear waves can be polarized and in anisotropic materials the modes have different properties. The two modes are usually defined as:

- a) the horizontally polarized (SH) mode;
- b) the vertically polarized (SV) mode.

The polarization direction is defined with respect to the specimen surface at the transducer index point.

3.13 poly vinylidene fluoride (PVdF)

Polymer piezoelectric material entering service in ultrasonic transducers.

3.14 hard copy

Representation of a TOFD B-scan or D-scan on a permanent medium such as paper rather than on a computer or monitor screen.

3.15 transducer

Active element of the probe allowing the conversion of electrical energy into sound energy, and vice-versa.

3.16 probe

Electro-acoustical device, usually incorporating one or more transducers intended for transmission and/or reception of the ultrasonic waves.

3.17 insonification

Flooding of the area of interest with ultrasound.

4 Principles of the method

4.1 When an ultrasonic wave interacts with a planar flaw it results in the production of diffracted waves from the tips of the flaw 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.

The diffracted energy is well suited for flaw detection as signals may be recorded from a range of flaws of different orientations using a single probe pair.

It is also of use in flaw sizing since the spatial (or time) separation of the diffracted waves is directly related to the height of the flaw. Normally TOFD uses compressional waves as these arrive first, simplifying the interpretation of the responses.

4.2 The concept of a time of flight approach to the detection, location and sizing of flaws can thus be developed. Omitting mode conversion effects (for the sake of clarity) and introducing ray paths marking the limiting routes for the ultrasonic energy, the kind of experimental set-up to be used is indicated in figure 3a). Other equivalent test geometries are shown in figures 3b) and 3c).

4.3 Energy from the lower tip or extremity arrives at the receiver later than that from the upper tip and this extra time delay is a measure of the flaw height. Moreover the pulses of interest are normally preceded by a pulse due to the energy which runs along the specimen surface and are followed by a reflection from the back wall of the specimen (see figure 4).

In this way it is usually possible to obtain unambiguous extra information on the location of the flaw within the thickness of the specimen. The echo pattern depicted in figure 4 is simplified if the flaw breaks the upper surface, blocking the lateral wave.

4.4 It is assumed that the ultrasonic energy enters and leaves the specimen at fixed points under the probes and separated by a distance $2S$ (see figure 5). This is a simplification of the true situation but is sufficiently accurate for many purposes (see 11.4). The time, T , taken for the ultrasonic energy to interact with a flaw tip at D and to return to the specimen is then given by:

$$CT = [d^2 + (S - X)^2]^{1/2} + [d^2 + (S + X)^2]^{1/2} \quad (1)$$

where

C is the ultrasonic velocity;

d is the depth of D below the specimen surface;

X is the displacement of the diffractor from the centre plane between the probes.

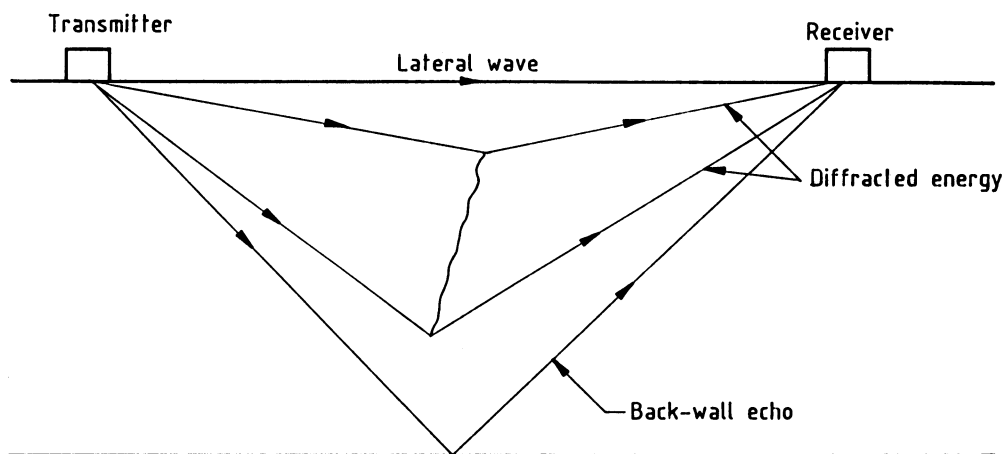
The value of T is a minimum when X is zero and in this simple case the expression becomes:

$$CT = 2 [d^2 + S^2]^{1/2} \quad (2)$$

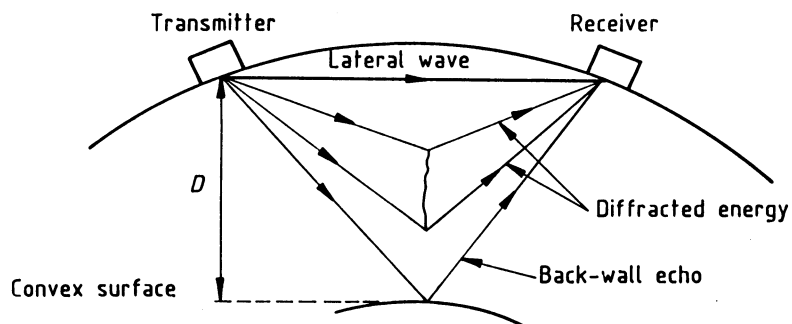
4.5 Commonly reference is made to the lateral wave response, i.e. the depths, d , of indications are calculated from the time-of-flight differences, T_D , between the lateral wave and the diffracted pulse. Hence:

$$d = \frac{1}{2} [T_D^2 C^2 + 4T_D CS]^{1/2} \quad (3)$$

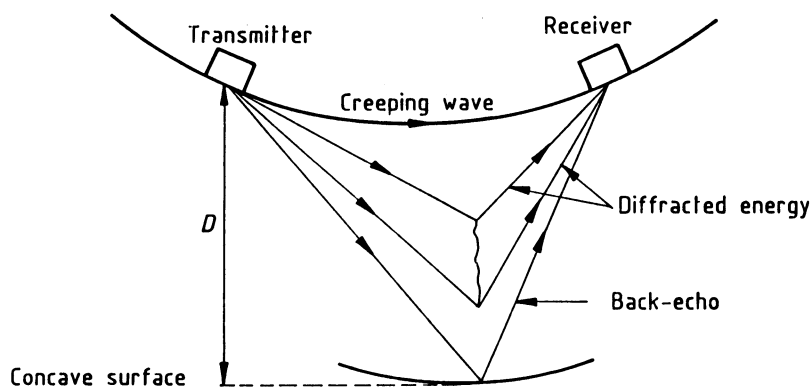
4.6 Equation (2) is used generally in the analysis of TOFD data and is thus of basic importance. The assumption that the flaw is positioned symmetrically between the probes introduces an error but, as is shown in clause 11, this can be arranged to have little effect on the accuracy of the estimate of flaw depth.



a) Flat specimen



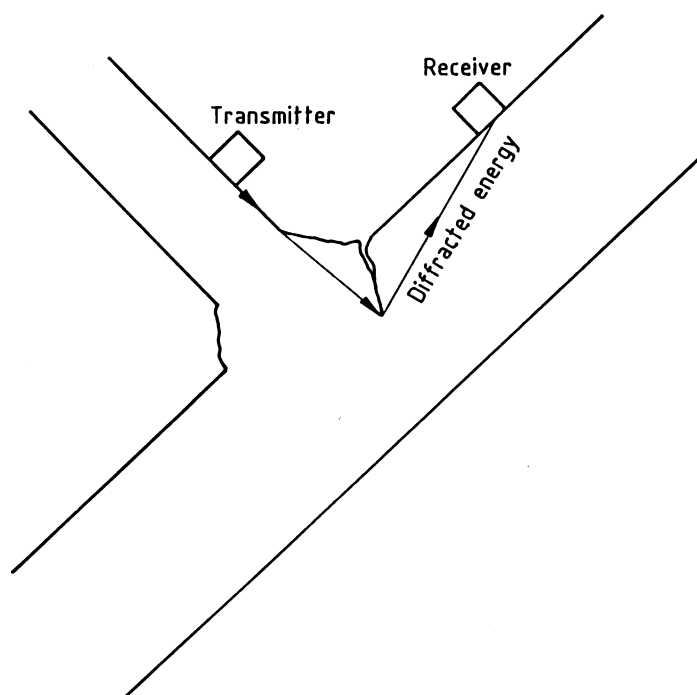
NOTE. Apparent depth D is less than the wall thickness.



NOTE. Apparent depth D is greater than the wall thickness.

b) Curved specimens

Figure 3. Diffraction from a crack-like flaw



c) Complex geometries, e.g. T-joint

Figure 3. Diffraction from a crack-like flaw (concluded)

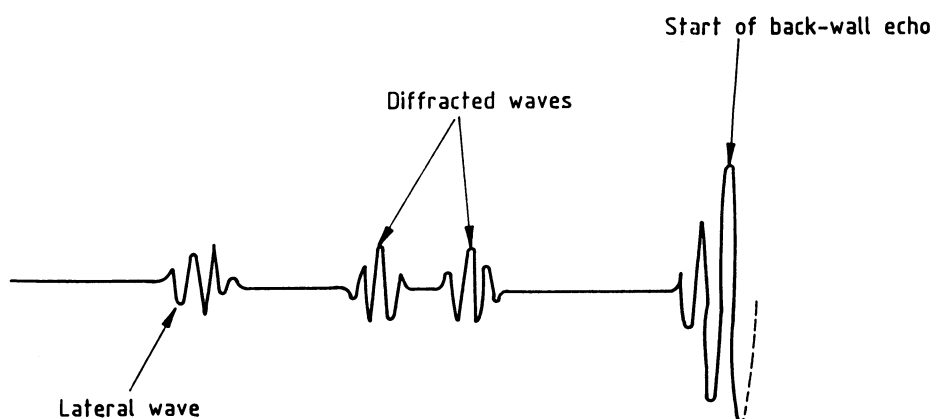


Figure 4. Typical pattern of pulses from an internal flaw

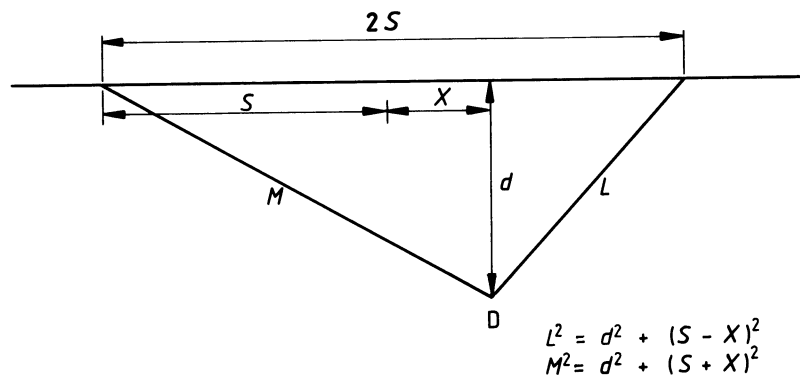


Figure 5. Generalized two probe testing geometry

5 Equipment

5.1 Electronics and data storage

5.1.1 In most circumstances an automatic data recording system is used. Manual and/or analogue equipment may be used for special applications. If additional benefit is to be obtained from post-inspection processing and if enhancement of data is required then use of a digital data recording system is necessary.

5.1.2 In order to achieve high quality repeatable results it is important to consider the pulser receiver electronics, the probes and connecting cabling. Important parameters for ensuring repeatability of testing include:

- pulser pulse rise time;
- pulser pulse amplitude;
- pulser pulse width;
- receiver lower, centre, and upper frequency limits;
- probe centre frequency; duration of transmitted pulse; cable and probe impedance; cable length.

5.1.3 Experience suggests that although conventional spike pulsers can produce good results, a square wave pulser allows a finer control and tuning for TOFD applications. The following parameters are important.

- A 200 V, 100 ns to 1.2 ps pulse width, which is suitable for the majority of applications.
- If the pulser is unipolar, the pulse width should be the minimum with as rapid a rise-time as possible. A nominal unipolar pulse width of 100 ns or less is achievable. A rise-time of 50 ns or less should be specified.
- If the pulser is bi-polar then the ideal pulse width is $\frac{3}{4} \lambda$ (typically 1 μ s to 2 μ s). The minimum pulse width is $\frac{1}{4} \lambda$ (typically 0.3 μ s to 0.6 μ s). The rise time should still be approximately 50 ns.

- A broadband receiver bandwidth of 0.8 MHz to 30 MHz.

NOTE. A range of bandpass filters within this is useful in many circumstances.

5.1.4 Because the received signals are generally very weak when working with TOFD it is essential to have higher than normal gain available with suitable signal to noise ratio. The overall performance of the system should be adequate to achieve the gain settings detailed in 6.5.

NOTE. A pre-amplifier may be desirable, particularly if long cables are required.

For automated systems best accuracy is achieved when the data samples are taken at equal spatial intervals. This can be achieved by synchronizing the movement of the scanning mechanism with the pulser receiver electronics/data recording system.

5.1.5 TOFD places strict requirements on the digitizing section of an automated recording system because errors in time measurement are crucial to the overall accuracy of the technique. A digitizer sample rate of 20 MHz to 25 MHz is adequate for the majority of applications. It is equally important to consider the time jitter of the sampling rate. This should be better than about 1 ns.

5.1.6 To interpret the TOFD data it is recommended that the observed signals are displayed as a B-scan or a D-scan (see figures 1 and 2). This may be done either as hard copy or on a monitor screen.

NOTE. A conventional flaw detector is not generally suitable for this inspection task but suitable commercial equipment is available. Advice on such equipment may be obtained from the British Institute of Non-destructive Testing¹⁾.

5.1.7 A common form of the required display comprises an amplitude related grey or colour scale representation of a series of digitized A-scans, plotted adjacently to form the complete image as a B-scan or a D-scan.

Care should be taken that adequate grey/colour scales are available to image the signals of interest.

NOTE. Experience shows that 64 grey scales are recommended as a minimum, for general use.

¹⁾ British Institute of Non-destructive Testing, 1 Spencer Parade, Northampton NN1 5AA.

5.1.8 From these B-scans or D-scans the data that needs to be extracted includes:

- a) the time delay of those echoes which may result from possible flaws;
- b) the length and shape of these echoes;
- c) the time delay of the lateral/creeping wave and back wall signals, if these are present.

While direct interpretation of the scans is possible it is normally essential that the data collected is archived in some agreed form.

5.2 Choice of ultrasonic probes

5.2.1 To obtain the utmost precision it is essential that the echoes have very good time resolution. Thus the use of unrectified pulses from short-pulsed transducers is recommended. The choice of probe is very application dependent and the following should be established:

- a) type of wave mode needed;
- b) timing resolution required;
- c) achieving the optimum resolution, e.g. by high-frequency or by short-pulsed transducers;
- d) effects of attenuation in the specimen;
- e) efficiency required to give detectable echoes in the test material;
- f) need for near-field operation;
- g) required beam width.

NOTE. The choice of each of the parameters generally represents a compromise between resolution, signal-to-noise and gain-in-hand.

5.2.2 The usual choice of wave mode is the compressional wave since this has the highest velocity. Echoes thus arrive before competing mode-converted echoes, provided that the probe separation, as defined by the probe index points, is in excess of $2D$ where D is the thickness of the testpiece (or depth of interest). The normal shear wave (vertically polarized) should rarely be used in this search and size role but pilot studies in individual cases may establish its suitability. The use of the horizontally polarized shear wave may be essential for some highly textured materials provided that suitable transducers are available.

5.2.3 The resolution of the technique in any particular application can be estimated from the known pulse length and equation (1). In practice the simpler equation (2) is often employed, being sufficiently accurate to define resolution limits. As an example, consider resolution of echoes from near surface flaws from the lateral wave signal. From the pulse length the first point at which a second similar pulse can be recognized may be estimated, for example, if the arrival times are separated by more than two cycles. This may be translated into time, i.e. $0.4 \mu\text{s}$ for 5 MHz probes. If this value is substituted into equation (2) the minimum depth at which a flaw tip echo can be

resolved may be estimated from the value of d . In other situations, such as the resolution of echoes close to the back wall echo, the time resolution defines the acceptable difference in the echo arrival times. Both arrival times are given by equation (2) with $d = D$ in the case of the back wall echo.

5.2.4 Improved resolution can be obtained by choosing higher-frequency probes or by selecting probes with short pulses. The former have a higher intrinsic precision but the latter are likely to be less affected by material attenuation.

5.2.5 The effects of attenuation and the probe power requirements are best evaluated on a representative test piece. It should be possible, using the desired equipment, to obtain a pulse from a representative flaw with an adequate signal-to-noise ratio. It should be recognized that such flaws are hard to simulate and, even if they can be detected and sized, may not demonstrate a similar capability for 'worst case' defects. The results depend on the test geometry as well as on the probe as is described in clause 6. Signal averaging, if available in the equipment, may be used to improve the signal-to-noise ratio.

5.2.6 It is important to determine whether operation in the near field of the probes is necessary. This is the range up to a distance $a^2/4\lambda$ where a is the probe diameter and λ is the ultrasonic wavelength corresponding to the probe centre frequency. This is because the pulse shape is likely to change in the near field, affecting any assumption made concerning resolution. Again measurements on representative specimens are an acceptable means of evaluating this.

5.2.7 The beam width of the probe can affect the nature of the data collected. In general, in a search and detection role, the beam should be chosen so as to insonify the entire section of interest so that all flaws show up. Because of the refraction of the beam at the material surface and the common use of high beam angles, this is not usually difficult to achieve. As amplitude is not used quantitatively, the sole aim is to demonstrate a reasonable signal-to-noise ratio at the edge of the beam with sufficient sensitivity to detect all flaws of concern.

Specific inspections may allow the use of narrower beams, e.g. if only far surface-breaking flaws are sought. This increases the beam intensity and may allow less signal averaging to be used.

Focussed beams should *not* be used in searching for flaws because the region of the material insonified is too small to provide a guarantee of detection. However they can be used for flaw sizing where they may provide extra information on tip location.

5.2.8 For most inspection applications probes with centre frequencies between 2 MHz and 10 MHz and diameters of 6 mm to 20 mm are suitable. For general use, a 5 MHz broadband 12 mm diameter probe is recommended as the starting point for probe selection. Probe selection for a given inspection application should take into consideration the objectives of the inspection and material characteristics. Modifying the probe characteristics has the following effects:

a) *increasing frequency:*

- 1) shortens wavelength;
- 2) improves resolution;
- 3) shortens time duration of lateral wave;
- 4) decreases beam divergence;
- 5) increases near field length;
- 6) decreases penetration (higher attenuation);
- 7) increases acoustic grain scatter;

b) *decreasing frequency:*

- 1) increases wavelength;
- 2) decreases resolution;
- 3) increases time duration and intensity of lateral wave;
- 4) increases beam divergence;
- 5) decreases near field length;
- 6) increases penetration;
- 7) decreases acoustic grain scatter;

c) *decreasing probe diameter:*

- 1) decreases output;
- 2) increases beam divergence;
- 3) decreases near field length;
- 4) decreases contact area, emission point closer to front of wedge;

d) *increasing probe diameter:*

- 1) increases output;
- 2) decreases beam divergence;
- 3) increases near field length;
- 4) increases contact area.

5.2.9 BS 4331 : Parts 1 to 3 may be used as a guide to the selection and calibration of individual transducers.

NOTE. It should be noted that this standard applies to angled shear 'SV' wave probes rather than the angled compressional wave probes commonly used for TOFD.

6 Setting-up procedures for flaw detection

6.1 Basic considerations

6.1.1 Given a particular inspection task, the first point to consider is the optimum probe configuration. This controls both the accuracy of the technique and the signal-to-noise ratio.

6.1.2 The TOFD technique in the two probe form used for defect location and sizing is that shown in figure 3a. In this the geometry of the testpiece is represented as a simple flat plate. This is clearly directly relevant to the examination of butt welds not only in flat plate but also in pipes and vessels. For longitudinal welds in curved components the inspection geometry is different (see figure 3b) but the same basic approach can be used noting that:

- a) the effective and true depths of flaws are different;
- b) on convex surfaces the direct signal runs across a chord and the creeping wave may arrive later giving a longer dead zone.

These factors affect the choice of the transducer separation and frequency.

6.1.3 For other testpiece geometries the same basic principles hold and quite complex structures can be evaluated using two probe TOFD without any special modification (see figure 3c). Special consideration may be necessary for some geometries.

6.1.4 In general, the inspector has some control over the relative placement of the probes and over the choice of probe. Using these choices the task is to ensure that the pulses of interest are observable and that the inspection leads to a sufficient accuracy. This is developed in 6.1.5 to 6.1.8.

6.1.5 The condition of the scan surface of the specimen may affect the precision of the results obtained. A good guide is that which would apply for conventional ultrasonics (see clause 8 of BS 3928 : Part 1). Thus machined, as-rolled or lightly corroded surfaces should all be suitable for the use of this technique. However pitted, heavily corroded or as-welded surfaces would normally give poor coupling over at least a part of the area to be scanned. Where scanning on the weld surface is required it is necessary to dress the weld cap.