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FUNDAMENTALS & APPLICATIONS FOR NON-DESTRUCTIVE TESTING

Although Time of Flight Diffraction (TOFD) has been an accepted ultrasonic test technique since the 1970s, it has only recently become a popular stand alone inspection technique that has merited qualification programmes geared to technician certification. This book, Ultrasonic Time of Flight Diffraction, is designed to meet and exceed ISO9712 training requirements for Level 1 and Level 2 certification. In addition, the book is an effective means of preparation for those wishing to achieve Level 3 in national or international certification schemes. Material presented in this book is intended to provide readers with fundamental principles of diffraction and practical examples of application, both without reliance on complex academic descriptions. This is achieved by use of clear graphic illustrations.

Discussed TOFD concepts are discussed include:

- Fundamentals of ultrasonic testing
- Tip diffraction theory as it applies to TOFD
- Hardware components including pulsers, receivers, filters, motor control, encoders and methods of data acquisition and display
- Digitisation of data and signal processing
- Methods of setting sensitivity, calculating indication depths, intrinsic errors and dead zones
- Calibration checks and methods of establishing inspection sensitivity
- Procedure and technique development with respect to applicable codes and standards
- Data analysis and reporting of TOFD inspection results
- Examples of industrial applications

It was my intention that this book would provide readers with a practical understanding of the application of TOFD.

Ed Ginzel

TECHNOLOGY EXPERTISE EDUCATION CERTIFICATION CONFIDENCE

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ULTRASONIC TIME OF FLIGHT DIFFRACTION

1st Edition

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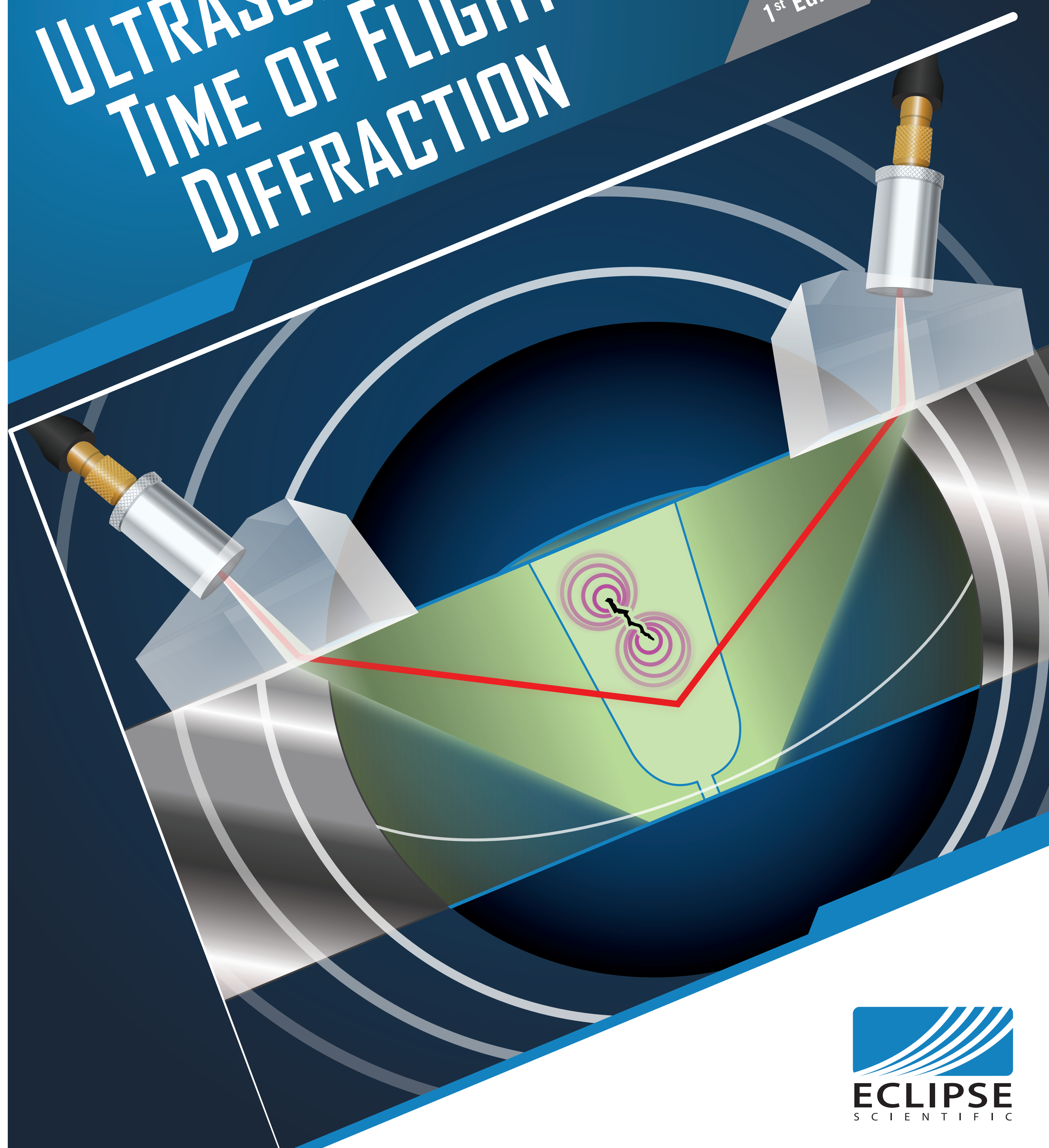

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CHAPTER (6): TOFD TECHNIQUE DEVELOPMENT

The principles of TOFD chapter described the basic layout of probes which are arranged on either side of a weld (the same principles can be used to carry out a form of corrosion tests where there may not be any weld to use as a reference). The image in Figure 2-10 shows the basic setup. However, aspects of the diffraction process along with the limitations caused by ring-time, the electronic equipment and the part tested need to be considered in greater depth when developing a TOFD technique for a specific application.

In this chapter, we consider some of the essential parameters when configuring the setup. In addition, we also consider variations on probe layouts.

6.1 PROBE SELECTION AND PLACEMENT

TOFD is usually applied to inspect the entire volume of a weld. In many cases, this can be done with a single pair of probes. The TOFD operator needs to then position the TOFD probe pair(s) in a way that ensures the area of concern is suitably ensonified. This requires consideration of several factors, some of which are interrelated. Design of the TOFD technique is a compromise of all the parameters considered.

Factors considered include (but are not limited to):

- Material tested
- Geometry of component
- Instrumentation available (single or multi-channel)
- Probes (size, frequency, angle (s), number of pairs)
- Detection requirements
- Sizing requirements
- Inspection speed and accuracy requirements

Applications involving complex geometries, such as T, K and Y joints, can be inspected using TOFD. However, the calculations involved will often require dedicated algorithms to determine indication positions relative to the test surface. These calculations are not standard and generally require customised software. Such calculations and applications are outside the scope of this handbook. For the purpose of this handbook only the more common configurations of basic butt welds will be considered.

Initially probe selection is based on the material tested. TOFD considerations for frequency are identical to pulse-echo. Coarse-grained materials and very thick materials will require lower frequencies to overcome the attenuation effect of scatter.

The probe size is then considered. It is also based, at least partially, on the material tested. To some extent larger probe dimensions produce a higher intensity pulse over a greater distance. But the need for divergence is better addressed using smaller probe dimensions.

The probe refracting angle is selected based on the geometry of the component tested. Very thick sections will require small refracted angles to ensure the back-wall can be detected. When the weld cap is not removed, it will present a restriction that may require a higher angle of refraction to ensure that the near surface is adequately addressed. Because of the large divergence in TOFD probes, the actual angles used may be off by as much as 5 degrees from the nominal and no significant deterioration of the technique will result.

In some cases, the thickness of the component tested is sufficiently large, so that no single probe pair can be expected to cover the entire thickness. Guidance on all of these items can be found in the several Codes and Standards now available for TOFD. A typical table found in the standards is reproduced here as Table 6-1. In this table we indicate the minimum number of zones that must be used to address the thickness of welds tested by a TOFD setup.

Table 6-1 Recommended TOFD setups for simple butt welds dependent on wall thickness

Thickness *t* (mm)	**Number of TOFD setups**	**Depth-range**	**Centre frequency *f* / MHz**	**Beam-angle (degrees) (α long.-waves)**	**Element size (mm)**	**Beam intersection**
6-10	1	0-t	15	70	2-3	2/3 of t
10-15	1	0-t	15-10	70	2-3	2/3 of t
15-35	1	0-t	10-5	70-60	2-6	2/3 of t
35-50	1	0-t	5-3	70-60	3-6	2/3 of t
50-100	2	0-t/2	5-3	70-60	3-6	1/3 of t
		t/2-t	5-3	60-45	6-12	5/6 of *t*; or *t* for α ≤45°
100-200	3	0-*t*/3	5-3	70-60	3-6	2/9 of *t*
		t/3-2*t*/3	5-3	60-45	6-12	5/9 of *t*
		2/3*t*-*t*	5-2	60-45	6-20	8/9 of *t*; or *t* for α ≤45°
200-300	4	0-*t*/4	5-3	70-60	3-6	1/12 of t
		t/4-*t*/2	5-3	60-45	6-12	5/12 of t
		t/2-3*t*/4	5-2	60-45	6-20	8/12 of t
		3*t*/4-*t*	3-1	50-40	10-20	11/12 of *t*; or *t* for α ≤45°

In Table 6-1, the column identified as "Number of TOFD Setups", refers to the number of TOFD probe pairs used

Having selected the appropriate probe pair parameters for the application, the operator then needs to position the probes to provide appropriate volume coverage. The effects of energy redistribution, upon diffraction, should also be taken into consideration.

The tabulated recommendations, for PCS values, indicate that the beam crossing points are generally set to two thirds through the test piece (for a single probe pair TOFD setup). For many applications the ⅔ guide is adequate; however, it is useful to confirm that the coverage on the far-wall will be adequate. When the TOFD inspection is carried out on a single V weld, the root area on the far-wall can be adequately addressed by a single probe pair. However, for a double V weld, the width of the weld cap on the far surface may not be adequately covered with a single probe pair.

As a guide to volume coverage, we can initially use the 24dB pulse-echo beam divergence calculations. When designing a TOFD setup, it is accepted that a symmetrical arrangement be used to indicate the beams. This, in spite of the fact that only one probe is transmitting. Since the probes used are to be "matched" with respect to frequency, size and angle, the reciprocity concept of transmitter and receiver can be assumed (i.e., probes can be interchanged with no apparent effect on the signal).

To verify the beam divergence and associated detection, a simple experiment can be set up. Using a small slit, 1.5mm to 2mm high in a 25mm plate (or a small side-drilled hole in a thicker section), the TOFD pair is placed symmetrically with respect to the slit on the opposite side. By moving the pair perpendicular to the slit (i.e., a parallel scan with PCS fixed) until the slit is no longer detected, the exit point of the transmitter positions for the peaked and dropped detection points can be compared. In most cases, the offset will be close to the calculated divergences, at the angles corresponding to the 20-24dB drop for that probe. When calculating the divergences, for a TOFD probe, the standard formula is used; with the medium used for calculations being the wedge material. The standard formula provides the half-angle of divergence. In order that adequate provision is made, for the angled incidence from the wedge, the rays are drawn from the probe element centre at the half angles, until the interface with the test materials (e.g., steel or aluminium). Then, Snell's Law is applied. All three rays are usually used, i.e., the front of beam, the back of beam and the centre ray. These are illustrated in Figure 6-1, where the front and back of beams are indicated by the shaded regions and the centre of beam is indicated by the red lines.

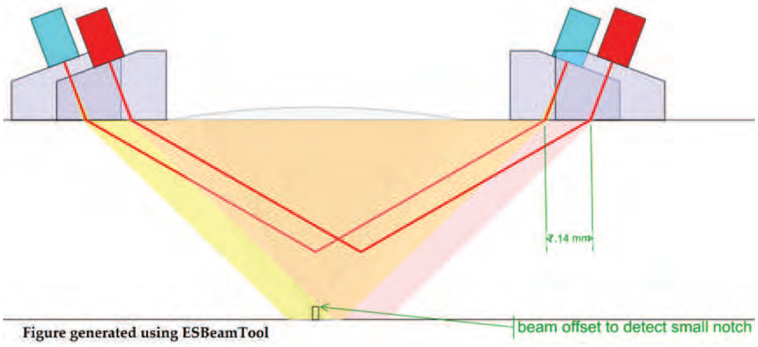

Figure 6-1 TOFD far surface detection verification

In the illustrated case, an offset of approximately 7mm would indicate the limits of detection from the root centre for the setup of a 5mm diameter 7MHz probe, for nominal 60 degree refraction.

In TOFD, the exit points of the wedges are used as the reference for setting the probe separations. The Probe Centre Separation is abbreviated PCS and used as the parameter of measure for probe placement. As noted, although only one of the probes in the pair is used in transmit mode, the centre ray that corresponds to the nominal refracting angle is drawn for both the transmitter and receiver probes. The crossing point is set based on these centre rays. This is used to determine the Beam

Intersection, referred to in Table 6-1. In Figure 6-1, the front of beam edge is not actually seen, as it glances parallel to the test surface. From this illustration, it can be expected that a lateral wave will be detected. For a probe with a smaller divergence (such as would occur for a 10MHz probe) the front of beam could be assessed by the detection of a side-drilled hole placed near the test surface. This is indicated in Figure 6-2. The lack of response from the side-drilled hole, when the probes are centred over the weld centreline, would indicate that the probe setup would not be suitable for flaw detections near the surface.

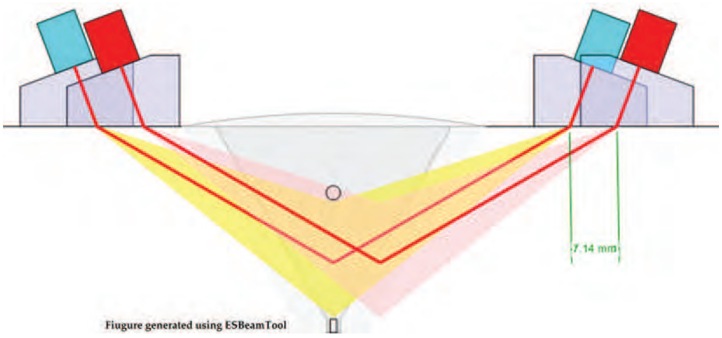

Figure 6-2 TOFD volume detection verification

Beam assessments, to establish coverage, are one of the functions of the calibration blocks and machined targets described above (in addition to setting sensitivity).

Relying on drawings of divergence boundaries to verify coverage is not a guarantee of flaw detection. Further consideration must be made for the pressure variation with respect to angle. Optimum diffraction energy is obtained when the included angle at the centrelines is approximately 120 degrees. This is based on diffraction theory for a vertical slit diffractor. EN 583-6 suggests that a working region of -35 degrees to +45 degrees from this value may still provide useful signals. This produces an incident angle range of about 8° to 38° with the vertical slit. However, at the 38 degree incidence, nearly all compression energy is lost, as it coincides with the critical angle. Therefore, examinations that rely on angles in this range (35-40 degrees) should be avoided.

In addition to the pressure drop associated with the transmitted beam, there is a further consideration for the beam pressure distribution. Figure 6-3 illustrates a pulse emitted from a probe striking a vertically oriented crack. This figure illustrates how a specular reflection occurs for the bulk of the beam. As it radiates off the crack, it has a directivity that includes lobes. The figure also illustrates the rings representing the diffraction off the crack tips. These diffraction rings are also subject to directivity effects.

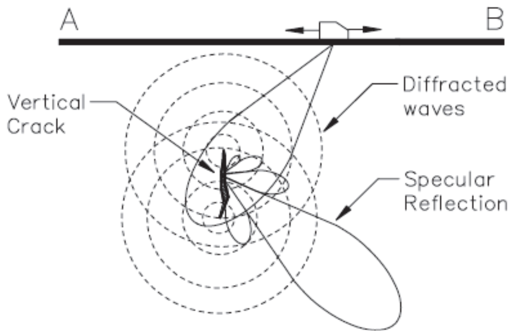

Figure 6-3 Reflection & diffraction directivity [28]

A similar directivity occurs for the diffracted waves. Figure 6-4 is reproduced from Charlesworth and Temple to illustrate the effect of incident angle on the relative amplitude of the diffracted signals in a TOFD setup. Incident angle theta is plotted as the horizontal axis and corresponds to the refracted angle emitted and received by the TOFD probes. From the curve, we see that a refracted angle, of about 65° incident on the upper and lower tips of a vertical planar flaw, will provide the maximum signal amplitude (pressure) at the receiver. The plot also indicates that, for the upper tip of a planar flaw, the signal amplitude drops to a minimum of about 13dB lower for a 0° incidence (this would be equivalent to a normal beam placed directly over the upper tip). For increasing incident angles over 65°, the amplitude will eventually drop to zero, at about an 85° incident angle. The amplitude response from the lower tip is more complicated. At about a 35° incident angle, the flaw face at the lower tip will provide the conditions for the first critical angle; and the signal amplitude drops to zero. Upon further decreasing the incident angle, some rise in the lower tip amplitude can be seen, to a maximum at about 18°. Further decreases in incident angle result in amplitude decreases to zero, at an incidence angle of zero degrees.

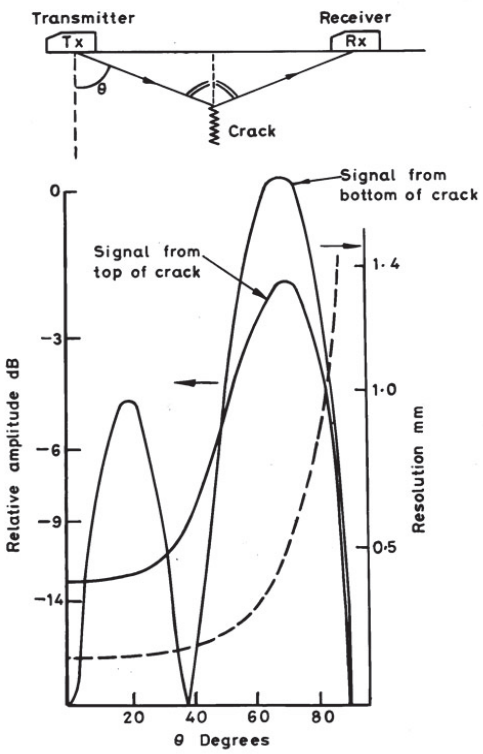

Figure 6-4 TOFD Tip signal amplitudes vs. Angle of Incidence (7)

The dashed line in Figure 6-4 indicates the resolution, theoretically achieved for a 5MHz probe on steel. The fact that amplitude drops off, for a particular range of angles within TOFD beam coverage, is further evidence of the need for multiple TOFD zones (setups) as component thickness increases.

The compromise requirements for TOFD configurations should now start to be apparent. In order to obtain optimum probe separation for maximum volume ensonification, a wide separation is used. Optimum probe separation, for resolving a separation between the upper and lower tips of a flaw, is when the total distance travelled is a maximum and occurs with a minimum probe separation. When considering the optimum diffraction pressure for detection of diffracted signals from flaws, a PCS, that provides a 120° included angle of the probe beam axes at the flaw tip, is required.

The recommendations in Table 6-1 indicate the beam intersections occurring at 2/3 the thickness of the zones. This results in an included angle of nearly 120 degrees. Because of the compromises that are required to obtain suitable coverage, resolution and detection amplitudes, the exact angle and PCS in Table 6-1 should be considered as guidance and the optimum combination of parameters is to be established based on the specifics of the application.

As noted previously, the precise angle used is not normally critical and deviation of 5 degrees is usually tolerable.

Under some conditions, where Table 6-1 indicates that one probe setup may be adequate to fulfil inspection requirements, the operator may still decide that more than one probe pair and more than one PCS may be required, in order to obtain improved coverage and resolution. Depending on the electronics and probe holders available, this may require more than one scan.

6.2 BASIC PROBE ARRANGEMENTS

When a simple plate is welded, the probe parameters can be selected to provide the required volume coverage in a single pass non-parallel scan. With guidance from Table 6-1 and consideration for the weld cap in a single V weld, typical setups can be modelled. Beam spread is considered essential in the single zone, so as to ensure adequate near surface coverage in proximity to the lateral wave. As weld thickness increases, the beam spread and suitable refracted angles are required to provide both the required volume coverage and the incident angles at the region of interest, ensuring adequate amplitude responses from upper and lower tip echoes.

6.2.1 SINGLE TOFD ZONE

Diameter	3
Frequency	10
Angle	70
PCS	71
Crossing depth	13mm
Max. angle	90°
Min. angle	50°

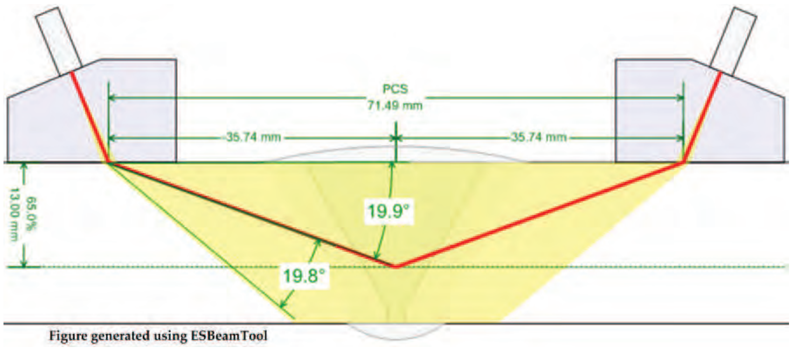

Figure 6-5 Single V 20mm wall technique

6.2.2 TWO TOFD ZONE

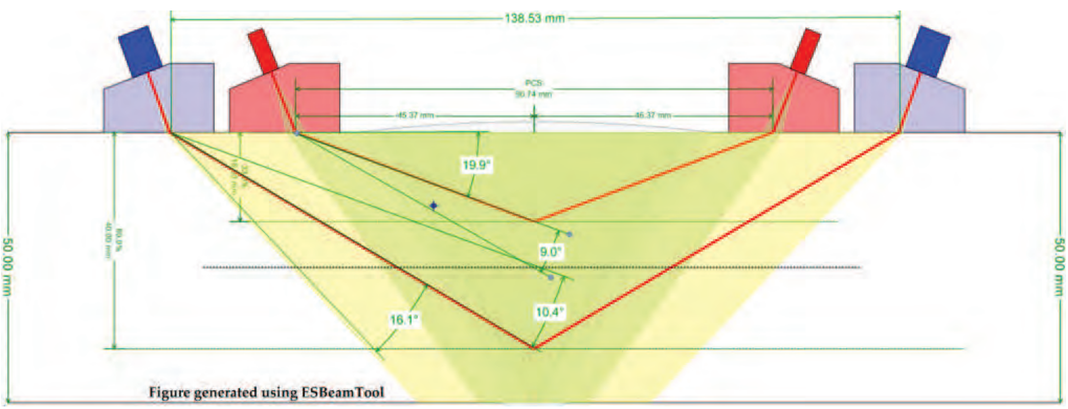

Figure 6-6 Single V 50mm wall technique

Diameter	Frequency	Angle	PCS	Crossing depth	Max. angle in zone	Min. angle in zone
3	5	70	90	16mm	90°	60°
6	5	60	138	40mm	70°	44°

6.2.3 THREE TOFD ZONE

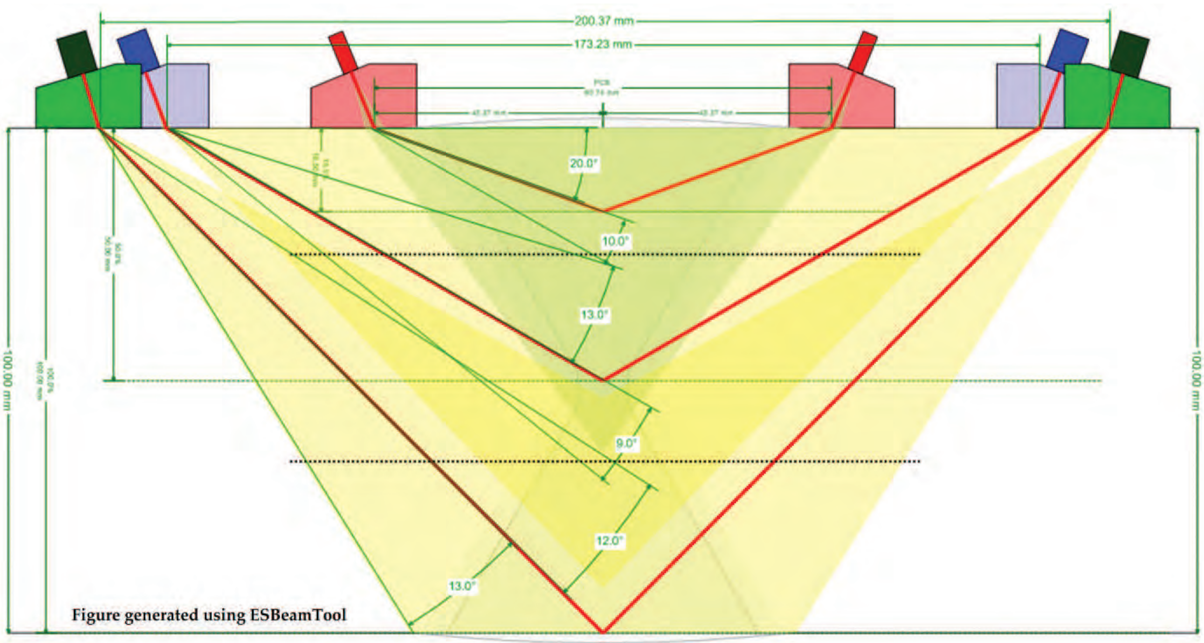

Figure 6-7 Double V 100mm wall technique

Diameter	Frequency	Angle	PCS	Crossing depth	Max. angle in zone	Min. angle in zone
3	5	70	90	16mm	90°	60°
6	5	60	173	50mm	73°	51°
6	5	45	200	100	57°	32°

Note: It was decided that the zone spacing would not be made equal for all three vertical extents. Instead, a near surface limit of 25mm depth was designed. This left a thickness of 75mm to address. When divided in half, each of the lower zones is 37.5mm high. The 2/3 crossing point in the zone from 25mm to 62.5mm is about 50mm from the surface. With the 6mm diameter 5MHz probe selected for the lowermost zone, the beam spread is getting close to the limit needed for coverage of the far surface. Guidance from Table 6-1 indicates that we can direct the crossing point at the full depth when using a 45° refracted angle. The curves, in Figure 6-4, indicate that this beam angle will suffer from weak lower tip signals if detected below the centre of beam. However, the sensitivity to the upper tip diffractions should still be adequate to provide flaw detections. If flaws that are located in this region require vertical extent sizing, it may require extra TOFD scans or the pulse-echo sizing technique applied.

6.3 ALTERNATIVE PROBE ARRANGEMENTS

For various reasons, the simple TOFD setup, with a matched probe on either side of the weld, may not be possible or adequate in all cases. The following are some examples of other considerations when setting up a TOFD inspection.

6.3.1 OFFSET SCANS

In the previous examples of TOFD setups, the probe placement was symmetrical at about the weld centreline. In some cases, this results in areas not being included in the inspection volume, especially on the far surface. A related problem occurs due to the locus of equal time and the far surface dead zone. When a specified minimum flaw size on the far surface is to be detected, it may require that the region of interest be close to the beam crossing centreline.

Figure 6-8 illustrates a 25mm double V weld with a single zone TOFD setup (3mm diameter 10MHz probe). The PCS has the 70° beams crossing at 2/3 depth. But, the beam coverage is seen to be inadequate to detect a relatively large 2mm deep toe-crack on the far surface. The image also illustrates the calculated dead zone (0.9mm) and the locus of equal time. Any flaws in the weld cap deeper than the 25mm plate thickness, less the far surface dead zone, would not be resolved from the back-wall signal (i.e., signals originating in the cap, deeper than 24.1mm would likely not be seen).

Even relatively deep flaws (like the 2mm toe-crack) will be missed, when scanning with the symmetrical setup in Figure 6-8, due to the locus of equal time. The pink arc at the bottom of the image in Figure 6-8 indicates the start of the back-wall ringing. The toe crack occurs at a time later than the back-wall arrival time, so it will be masked by the ringing.

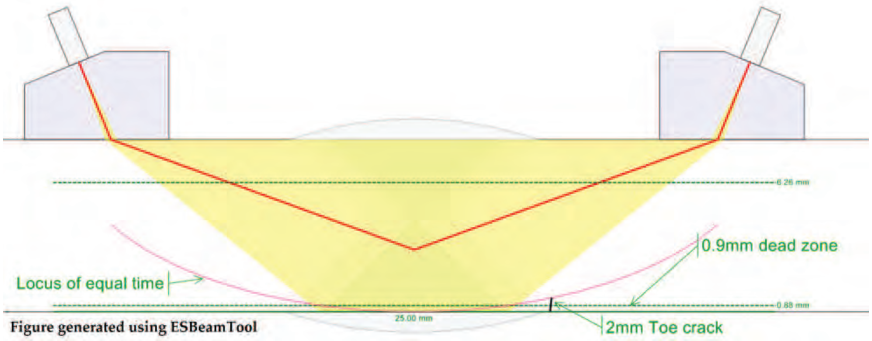

Figure 6-8 Double V 25mm wall with 2mm toe-crack on opposite wall, not detected

The solution to this problem is the offset scan. By offsetting the probe pairs, from the centreline of the weld and making 2 scans (or using 2 pairs of the same probes), the toe crack will be detected on the offset that places the crack above the locus of equal time, as illustrated in Figure 6-9.

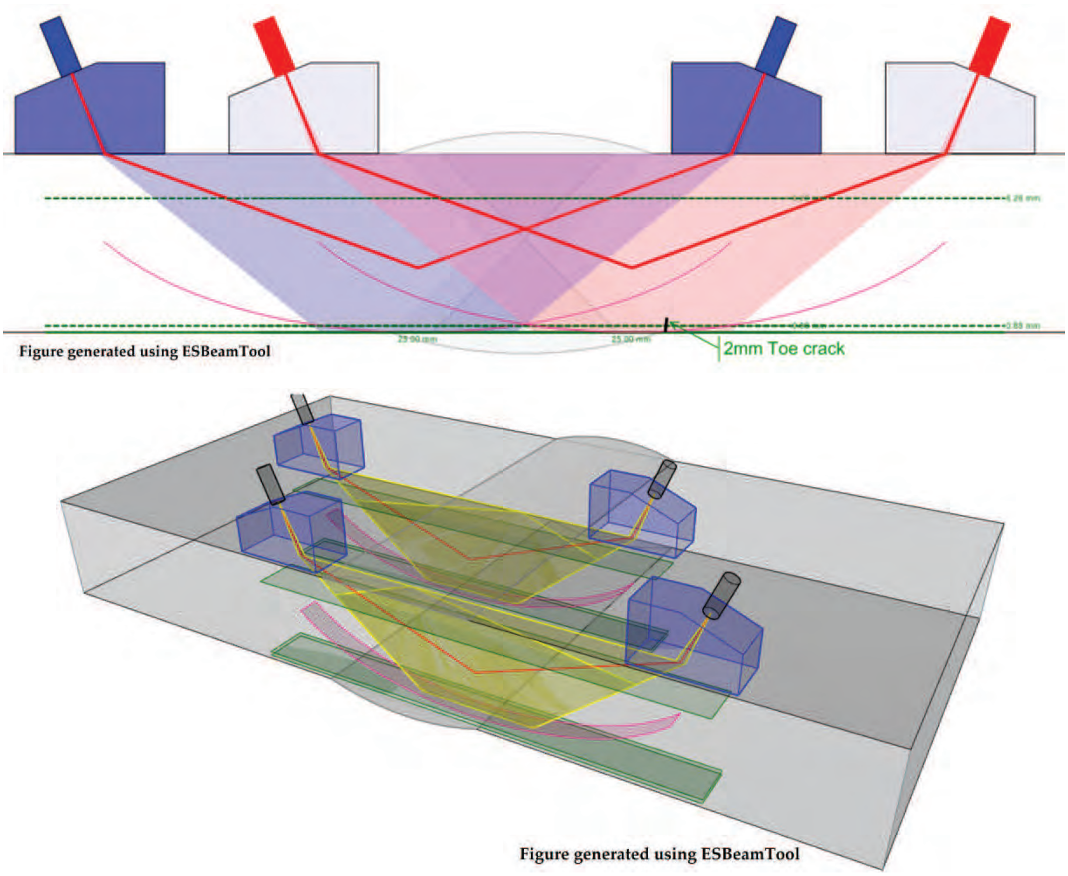

Figure 6-9 Offset scan with 2mm toe-crack on opposite wall detected

6.3.2 SAME-SIDE TOFD

In the description of the principles of TOFD, in section 2.3, the TOFD technique was defined as being two probes arranged in opposition. There is a possible variation of that configuration called one-sided TOFD. This is a tandem arrangement of the TOFD probes on the same side of the weld. Under certain conditions this can have an advantage, in that access can be limited to a single side for some geometry. Placing a pair of probes facing a weld, with some spacing between them, it is possible to collect back-diffracted signals. A noticeable difference with one-sided TOFD is the lack of reference signals as with the traditional TOFD. With both probes facing the same direction, there is no lateral wave and no reflected back-wall. Refracted angles need not be identical and the display is not as straight forward to interpret for depth assessment.

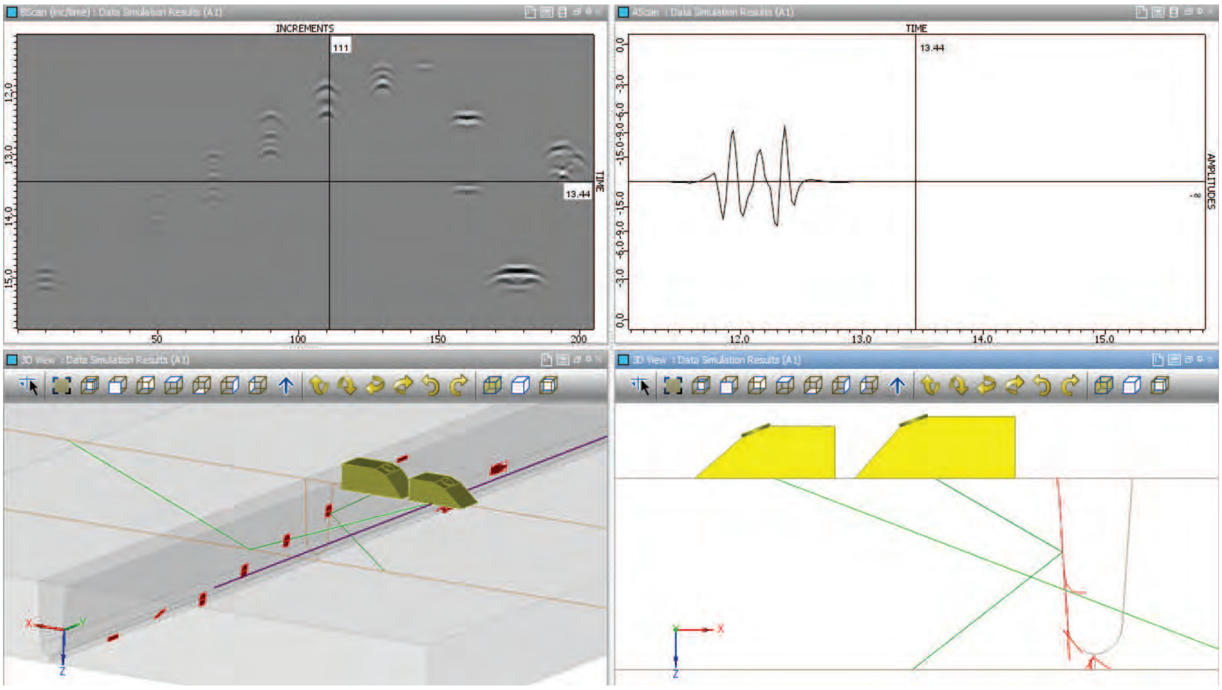

Figure 6-10 Same-side TOFD layout and responses

Figure 6-10 illustrates the setup and the sort of B-scan display that results from the same-side TOFD configuration. Note that the root and cap signals are not possible to reference with respect to the lateral wave and back-wall signals. A mathematically calculated top and bottom would be required to assess the true depths of the indications.

6.3.3 SPECIAL PROBES FOR NEAR SURFACE FLAWS

The presence of the lateral wave ring-time has long been considered an impediment to TOFD. Lateral wave removal is available on most systems, but not always used by the technician. Therefore, when a scan is made and no abrupt changes are seen in the lateral wave, the assumption is made that no near surface flaws exist. In some cases, this assumption is not adequate for the codes. Extra scans are then required to investigate the upper region of the component.

Three options are generally considered feasible for ultrasonic tests; high angle shear wave with a dual element probe, a full skip pulse-echo scan or a high angle compression wave in pulse-echo mode. A simple pulse-echo scan, limited to monitoring the upper surface of a weld, is useful if it is feasible to restrict the region of interest to just a few millimetres on either side of the toe of the weld. This option becomes less attractive for very thick sections. For example, when a weld is made in a plate 100mm thick, the sound path for even a 45° beam is 280mm to the top surface. The resulting beam spread at that distance will make the detection relatively imprecise. An effective option in some cases is to use a high angle dual element probe designed for use in transverse mode. A popular option to the dual element probe is to use a high angle compression mode probe in pulse-echo. In some cases, users have even configured the hardware to fire the TOFD probes, first in transmit-receive mode for the TOFD data, and then in pulse-echo mode to generate the so-called creeping wave (which is nothing more than the compression mode glancing along the near surface).

6.3.4 PA TOFD

With adequate electronics built into the system, phased array probes can also be operated in a TOFD mode.

The probe arrangement is identical to the single element configurations, with a probe either side of the weld. An appropriate number of elements are then selected to pulse and receive in each probe. The number of elements and the refracted angles are selectable from the software menu in the phased array system. The resultant signals are no different from those seen using single element probes with similar parameters. Figure 6-11 illustrates a phased array setup for TOFD, and Figure 6-12 illustrates the B-scan collected.

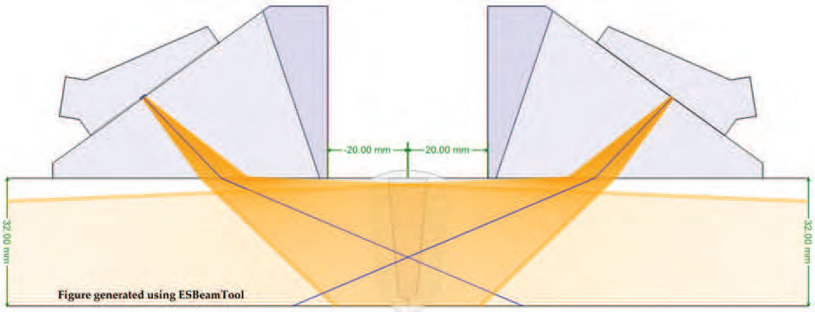

Figure 6-11 PA TOFD layout with 7MHz probe and 4 elements at 0.6mm pitch

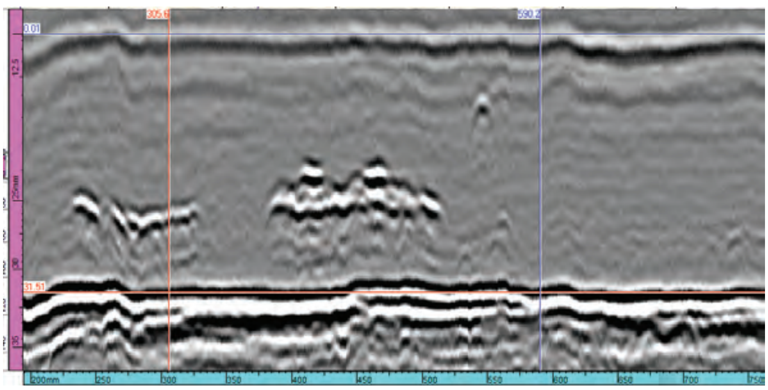

Figure 6-12 Sample B-scan from PA TOFD setup (not noticeably different from mono-element)

Where multiple zones are used, there can be a limitation for phased array TOFD. A single phased probe pair may be able to configure two zones, but it will be limited to the single frequency of the probe. Applications with phased array systems often take advantage of the combined pulse-echo and

TOFD potential of the phased array, but may augment the phased array TOFD with a mono-element TOFD, using a dedicated small diameter high frequency probe pair for the uppermost TOFD zone.

6.3.5 IMMERSION AND GAP TESTING OPTIONS AND ISSUES

Replacing the refracting wedge, in a TOFD configuration with water, is perhaps not common, but it is feasible. With water or similar liquid, as the refracting material, issues of intermittent coupling are eliminated.

Immersion testing implies the test piece is immersed in the coupling liquid. The probe may be partially or completely immersed, as well. The transducer uses the couplant as a delay line. Being fluid, the angle and time in the refracting medium are infinitely adjustable.

The biggest advantage to coupling by immersion is uniformity. Contact coupling always has fluctuations in proximity and amount of couplant under the shoe. Immersion testing does not have this variable contributing to amplitude variation.

Incident angle is easily changed in immersion testing and is not limited to discrete angles, as is the case for contact tests. Since no direct contact to the part is made, no wear occurs and contouring of the probe is not necessary.

Probes used for immersion testing are relatively straight forward. Except for waterproofing of electrical connections, construction of the basic unit is the same as for contact probes. Since no wedge is used, the probe housings need not incorporate wedge adapters; and the elements can be mounted in a housing with little or no protective face. In fact, PVDF (polymer) probes are constructed with gold electrodes exposed to the water (providing very high frequency pulses).

Focussing of the beam is simplified in immersion techniques. Cast synthetic resins and moulded ceramic or polymer elements allow straightforward focussing.

When the immersion fluid is restricted to a small volume in front of the probe, the immersion technique is more accurately called gap testing. Devices are designed to provide a fixed gap between the probe-face and test part. The gap is filled with water (or similar couplant). Couplant can constantly be fed into the gap by a pump or the test may be configured to prevent water loss as the part is moved past the probes. Plate and tubular products are often tested using these devices.

When the couplant is trapped in a small cavity and provides a fixed water path, the device is sometimes termed a bubbler. Depending on surface conditions and thickness, the gap may be several microns or several centimetres. Relative movement, between the probe and part coupled with surface tension, will ensure some water is always lost, so a reservoir must be drawn from. A single probe with gravity fed water-flow can be used in manual scanning or the same principle can be employed for automated systems with multiple probes. Several gap testing methods are illustrated in Figure 6-13.

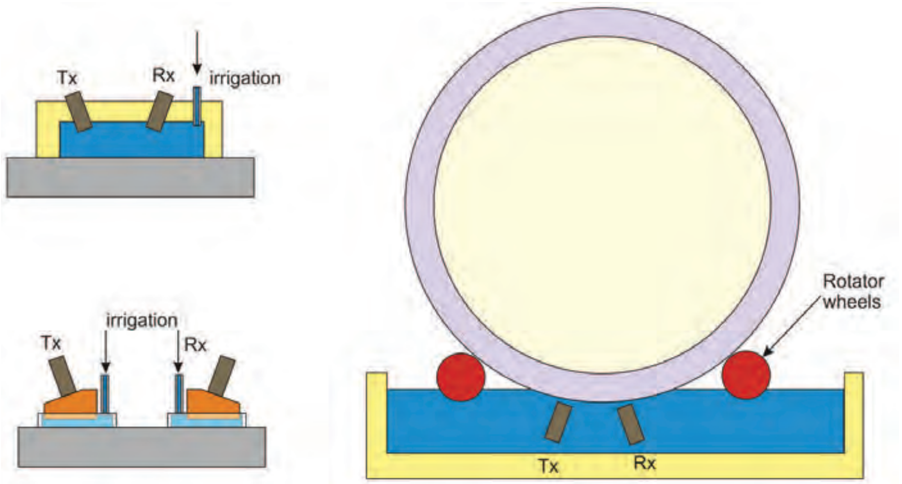

Figure 6-13 Gap testing options

Of the illustrated options for gap testing in Figure 6-13, the one indicating the probes with wedges in a holder being fed with irrigation (lower left) is essentially the same as most contact setups where water is pumped through irrigation channels in the wedges. When the gap is used, but is not sufficiently large so as to avoid sound bouncing between the wedge and the test piece, a gap multiple occurs. This appears as a double (or treble) lateral wave. Use of gap testing with wedges and just carbide wear tips should avoid any gap, i.e., carbide tips should be adjusted to ensure the tips are flush with the wedge surface. In these applications, the purpose of the carbide wear tip is to reduce wear, not to provide a gap. The result of the gap when carbides are used is seen in Figure 6-14.

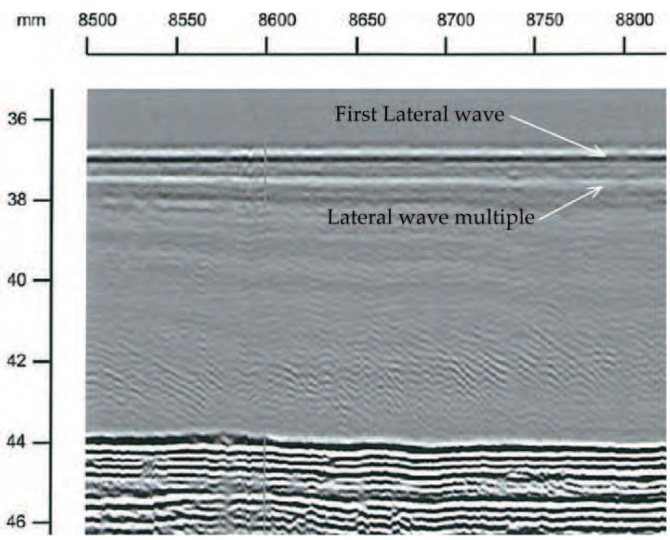

Figure 6-14 Lateral wave multiple due to excessive gap