DESIGN AND APPLICATION OF LOW-FREQUENCY TWIN SIDE-BY-SIDE PHASED ARRAY TRANSDUCERS FOR IMPROVED UT CAPABILITY ON CAST STAINLESS STEEL COMPONENTS

M. Delaide, G. Maes (AIB-Vinçotte International, Brussels, Belgium)
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Abstract

Due to their coarse-grain structure, austenitic stainless steels in general, and cast or welded components in particular, can strongly affect the performance of ultrasonic examination techniques. The major problems encountered are beam skewing and distortion, high and variable attenuation, and high background noise.

For many inspection problems involving austenitic components, the best examination performance has been achieved using broadband twin-crystal compression wave (TRL) angle beam probes, due to pseudo-focusing effect resulting from the convolution of the transmitter and receiver beams. Recently, the use of curved piezoelectric elements, providing an additional optical focusing effect, has been observed to considerably enhance the signal-to-noise ratio in the focal zone of the transducer.

On the other hand, the phased array technology has already demonstrated its advantages in various industrial applications : the possibility to apply various examination angles during a scanning sequence while using one single probe, and its ability to electronically focus the acoustic beam at one or more given depths.

This paper shall present an innovating phased array transducer design for the examination of cast stainless steel components, combining the intrinsic advantages of conventional highly-damped low-frequency TRL transducers and the versatility offered by the phased array technology. Various aspects of the twin side-by-side array design, as well as the dedicated procedures that were developed for the characterization of the probes shall be addressed.

Practical trials were performed on artificial flaws in thick wall cast stainless steel specimens, to illustrate the excellent performance of the prototypes in terms of signal-to-noise ratio and lateral resolution. The examination data shall be analyzed, and the UT capability of the twin side-by-side phased arrays shall be compared to the results obtained with conventional TRL transducers on the one hand and single-crystal phased arrays on the other hand.

Introduction

Ultrasonic testing of stainless steel components

In most austenitic stainless steels, cast or welded components in particular, the grain coarseness highlights the elastic anisotropy of the crystallographic lattice, inducing several strong disturbances in acoustical wave propagation, such as energy scattering and acoustic ray deviations. Further more, the macroscopic inhomogeneity of the components causes the steel structure and the associated effects on ultrasound to vary locally (1).

If conventional, standard or phased array, ultrasonic testing (UT) probes are used on austenitic materials, the various phenomena encountered can be transposed in the UT-language as beam skewing and distortion, high background noise, rapid extinction of the signal with depth and filtering of high frequencies. As a consequence, conventional UT is less applicable on these materials because of the commonly very low signal to noise ratio achieved and because of the uncertainty about flaw location. To overcome these difficulties, several inspection techniques have been developed the last two decades. In the field of advanced UT probes in particular, the best examination results have been achieved by mean of a technical compromise following essentially four design guidelines.

The first rule is to use wavelengths larger than the grain size of the component: the nominal frequencies to be applied should typically range from 0.3 to 2MHz.

The second rule is to carefully select wave modes propagating satisfactorily in the component: compression waves (L waves) are mainly used, but shear horizontal (SH waves) generated by electromagnetic acoustic transducers (EMAT) and even low-frequency shear vertical (SV waves) can be considered.

Third, heavy damping should be applied, to assure a good depth resolution (lower than one and a half wavelength) and a broad bandwidth (to avoid side lobes and perturbing interference's in the acoustical field and to attenuate the filtering effect and the background noise of the material). The bandwidth of an optimal probe configuration is typically larger than 90 %.

The last rule is to use techniques that reduce the beam width, in order to improve the lateral resolution and to enhance the sensitivity: transmitter / receiver twin element search units (commonly called TRL probes), focusing probes and, more recently, phased-arrays are the most widely used techniques.

Principles of standard TRL search units

TRL (Transmitter / Receiver side-by-side L waves) search units, as shown schematically on figure 2, are the most widely used technique for coarse grain materials. The apparent acoustic beam results from the convolution of the sound fields of the separate transmitter (T) and receiver (R) piezoelectric elements. A quasi-focusing effect in the beam crossing region is obtained, substantially improving the signal-to-noise ratio in a limited depth range (2). The main characteristics of TRL probes are the following:

- the maximum sensitivity and the minimum beam width (Focus and dF on figure 2) are typically situated in front of the geometrical crossing point, in a -6dB range to be compared with the -6dB focal zone of a focusing probe;
- the apparent angle beam of the probe decreases slowly with the depth;
- the absence of a “dead zone” allows for covering depth ranges starting from right under the scanning surface : the TR configuration avoids the perturbations coming from the interface and wedge internal reflections, after the start echo.

Further, the use of curved piezoelectric elements, providing an additional optical focusing effect, enhances the signal-to-noise ratio in the pseudo-focal zone of specially designed transducers. This was demonstrated to be very suitable for advanced sizing methods such as the flaw tip diffraction technique (3).

Principles of the phased-array technique

Phased array technique stands for steering of the ultrasonic beam by means of electronic applied delays on the segments of a probe array. These delays are applied during emission and reception of the ultrasonic signals. Ultrasonically spoken, phased array behaves similar as a conventional probe. In the case of a conventional probe the beam angle is obtained by using an angled wedge. The obtained refracted angle is defined by the wedge angle and the propagation speed in the wedge and in the inspected material (Snell’s law). Considering the time domain (see figure 1.a), one can also observe that the ultrasonic wave generated by the crystal travels through the wedge and hits the wedge-material interface. Following the Huygens principle, the points lying on the interface will generate a spherical wave that will travel into the material. Due to the time delay introduced by the wedge, the time of emission (at the interface) is different: the waves occurring from the shortest wedge path will start propagate first into the material while these occurring from the longest wedge path will start propagating last. At a given location in the material all the waves will be in phase and will continue propagating into the material while creating a wave front. The wave front travels into the material at a given angle (refracted angle) following the delays that occur at the interface level. If the wedge angle or the propagation velocity of the wedge is changed, the delays are different and consequently a beam with another refracted angle will be generated.

At the reception of a signal, the wedge behaves also as a delay generator. Waves generated by a punctual source (see figure 1.b) will travel through the material and hit the interface at different moments in time, depending on the distance from the source to the interface. Also here, the points on the interface will generate spherical waves that will travel in the wedge material. Due to the propagation delays in the wedge, only the waves that are in phase will be “summed” on the crystal surface and will yield a significant signal. Waves generated by punctual sources situated “outside” the beam will not arrive in phase on the crystal surface and will be attenuated after summation. Changing the wedge angle and/or wedge and material propagation speed will thus change the delays and consequently the orientation of the sensitivity field of the probe.

It can be easily understood that a similar mechanism applies to the generation and reception of a focused beam.

As explained above, the beam angle and focusing point are obtained by adding delays in the sound path. In the case of a conventional probe this is realized by using wedges or lenses. In the case of phased array (see figure 1.c), the crystal is cut in small parts, called elements, and for simplicity in this example, directly applied to the interface. Each element is excited with a separate pulse that is electronically delayed. Assuming very small elements, each of them will generate a spherical wave, and a wave front similar to the one obtained with conventional technique will be created into the material. Changing the delay-set, also called the focal law, will change the angle.

At reception (see figure 1.d) the received signal is digitized and delayed for each element following the same “law” and then summed. Only signals that “satisfy” the delay law will be in phase after the delay is applied and will yield a significant signal after summation. Signals received from other locations will be out of phase and consequently be significantly attenuated after summation.

The same principle applies to the generation and reception of a focused beam.

Phase array technique allows thus to steer the angle and to set the focusing depth dynamically by software. Since no mechanical movement is involved, the depth and/or angle can be changed at each firing. The used R/DTech Focus system (see figure 10) allows changing these parameters at a rate of 20 KHz.

Design of twin side-by-side phased array probes

The basic idea is to optimize the UT examination of austenitic steel components and welds by developing heavily-damped, low-frequency, TRL phased array probes offering the possibility of sweeping the angle beam and varying the focal depth. Considering the various geometrical conditions and the local variations of ultrasonic propagation, this new design aims in particular:

- To simplify on-site application, avoiding multiple probes and the associated complicated mechanical settings and heavy manipulators,

- To decrease scanning and manipulation time,
- To systematically apply the best-fit angle and focus settings.

The design principle of the TRL phased array (TRL PA) probe is illustrated on figure 4. The general configuration is the same as the standard TRL shown in figure 2, but transmitter and receiver consist of two linear arrays (two arrays of 4 elements on the example, giving a total of 16 separate UT channels). The phased array technology allows for modifying the probe characteristics by changing the incidence and skew angles of the transmitter and receiver beam and by changing simultaneously the focusing depth.

The angle beam of the developed TRL PA can typically be set from 0 to 60 degrees (0° to αmax in figure 4). Further, the array matrix is designed to provide, for each angle αi, depth focussing from near the surface (Fi min) to a maximum corresponding to the local pseudo-near field (Fi max); the total dimensions and shape of the transducer are selected to provide the desired lateral resolution and depth range.

Instead of one sensitivity curve describing the standard TRL probe (chart of figure 2), a TRL PA probe is defined by a family of normalized curves, giving, for each angle beam selected in the range 0° to αmax, the data of the optimal focal settings (chart of figure 4). Each of these curves is in fact the envelope of a basic family of sensitivity curves, parameterized, for the selected angle, by increasing focal depth settings.

By the same principle, an optimized beam width curve can be established per angle and be put in relationship with the sensitivity curve (chart of figure 4).

The principal differences between a TRL PA (figure 4) and a standard linear PA probe (illustrated on figure 3) are the absence of a dead zone, the possibility of lateral beam skewing (enabling configurations without axial symmetry) and the improvement of the lateral resolution.

Fabrication and characterization

Fabrication

Three models of TRL PA probes have been manufactured by AIB-Vinçotte International (AVI) up to now. The nominal frequencies are 1 and 2 MHz and the number of elements ranges from 44 to 64 (details given in table 1).

Industrial multi-core coaxial cables and connectors, piezo-ceramics and sawing devices were purchased from specialized suppliers. The backing materials, acoustical insulation, connection and moulding techniques previously used for the fabrication of standard TRL probes were successfully applied in the manufacturing process of the phased-array probes.

For instance, in order to obtain a short pulse length and a large frequency bandwidth, low mechanical quality factor piezoelectric ceramics were used, together with a high density backing (density > 11 kg/dm^3).

The housing of a TRL PA probe is moulded in hard polyurethane, a light and reliable design commonly used for nuclear site applications with standard TRL probes. Water tubing and mechanical devices are foreseen in order to allow for automated scanning (see figure 5).

The roof and incidence angles of the wedges are designed to generate L waves in the range of 0 to 60 degrees. Transmitter and receiver wedges are acoustically insulated to obtain a low level of internal reflections.

The array design (width and spacing of the elements) has been modeled and optimized (elimination of side lobes) by using the “PASS” software provided by R/D Tech.

Characterization on carbon steel test blocks

The probe characterization is performed on two flat carbon steel blocks : one block offers an infinite flat reflector inclined at 45°, and the other one contains several 4 mm diameter side-drilled holes with a depth spacing of 25 mm.

Sensitivity and beam width curves are recorded on side-drilled holes. The obtained results are in excellent agreement with the “PASS” software simulations and clearly show that:

- The beam deflection is effective from 0 to 60°,
- Narrow beams are achievable (less than 7 mm beam width for 1 MHz),
- Focussing beyond the pseudo near-field depth is not efficient.

The cross-talk measurement, which expresses the electrical and the acoustical coupling between adjacent elements, yields an average value of about –47 dB.

To evaluate the frequency bandwidth, the echo from an infinite flat reflector inclined at 45° is recorded statically. Figure 7 shows the non-rectified ultrasonic signals of the three TRL PA probe types; 95 and 117% bandwidth is achieved for the 1 MHz probes and 160% for the 2 MHz probe.

An example of a TRL PA standard characterization data sheet is given in figure 6.

Assessment of UT capability on austenitic steel

Test specimens

Two austenitic stainless steel calibration blocks, called here after PCM and NG, were used for the capability assessment.

The Pumpcasing Cast Material (PCM) block, is made of statically cast stainless steel (material: SA 351 Gr CF8A, dimensions: width 250 x length 300 x height 200 mm). Two artificial flaws have been investigated from the flat surface: a 5 mm diameter side-drilled hole at a depth of 50 mm (referred to as SDH5 D50), and a diameter 7 mm flat bottom hole at a depth of 50 mm, inclined at 45 degrees (referred to as FBH7 D50).

The Narrow Gap (NG) block (dimensions: width 330 x length 530 x thickness 80 mm, outside radius 450 mm), presents a narrow gap weld in the center, dividing the specimen in a "Safe-End"-side (SE), made of wrought stainless steel (WSS), and a "Cast"-side, coming from a statically cast stainless steel elbow (CSS). The reflectors investigated in this block are 4.8 mm diameter side-drilled holes (SDH4.8), machined tangentially at a depth of 20, 40 and 60 mm, measured from the external surface. They are situated in the cast material, in the heat-affected zone of the NG weld, and are insonified through the weld, from the SE side.

Equipment

The probes used for the trials are described in table 1.

UT data acquisition was performed with the equipment that was also used for the characterization measurements: R/D Tech FOCUS phased array system (figure 10), R/D Tech TOMOVIEW software and a mechanical{X,Y}scanner equipped with position encoders.

Data recording

PCM Block. Comparative measurements between the two 1MHz TRL PA, the focused TRL and the PA probe have been carried out on SDH5 D50 and FBH7 D50 described above. The results are presented in table 2. Figure 8 shows A-and B-scan images recorded on FBH7 D50 with the three probes having comparable aperture size.

NG Block. The three SDH4.8, mentioned hereabove were insonified from the SE-side with the two TRL PA and the TRL probe. Figure 8 compares the B-scan images recorded with a TRL PA and a focused TRL probe of similar size.

Discussion of the results

The PA probe is able to detect reflectors in cast stainless steel material, but the signal-to-noise ratio (SNR) is poor due to the importance of the dead zone (internal reflections are present up to 60 mm depth). So, in the depth range where the focalization is efficient, the probe internal noise is to high to provide a good detection performance.

The TRL PA TS45 1 6A1 and the conventional focused TRL TS 45 1 635 have a similar behaviour in the cast material: no interface echo or internal reflections, no relevant differences in SNR or beam sizes on SDH and FBH. Actually, at equal focus depth and beam angle as the conventional TRL version, the TRL PA version is absolutely comparable.

Compared to the TRL PA TS45 1 6A1, the TS45 1 8A2, bigger in shape, performs better on SDH but not on FBH at a depth of 50 mm. At the expense of an inferior lateral resolution, its sensitivity on small reflectors is enhanced, particularly in the depth range 60 to 80 mm. An interface echo is perceptible in the first 20 mm of depth, the amplitude of which decreases with increasing beam angle. This probe should be considered as complementary to the TS45 1 6A1, and is to be used whenever more sensitivity is required.

Conclusions

The low-frequency TRL phased array probes discussed in this paper provide various improvements with regards to both standard TRL probes and linear phased array probes, for applications in cast austenitic steel structures. The main advantages of the design are the following :

1. TRL PA probes have no significant dead zone;

2. The global depth of field, obtained by successive depth focussing, is optimal;

3. The sweeping of the TRL angle beam enhances the capability for detection and evaluation of flaw indications, specially in challenging materials presenting a lack of structural homogeneity;

4. The lateral resolution is optimal throughout the complete depth range;

5. Heavy damping of the piezoelectric elements improves the axial resolution and the signal-to-noise ratio.

The results of the test programme on austenitic steel specimens with the manufactured 1 MHz TRL PA probes have shown that the achievable depth range is 20 to 80 mm, the angle beam sweeping range 0 to 50 degrees, and the minimum beam width in the incidence plane 12 mm.

The availability of industrial fabrication and characterization methods, together with the promising results of the test programme demonstrate that the developed TRL PA probe is now ready to be used for on-site applications.

Further development of a 0.5 MHz version should allow for an increase of the depth range, but this also requires a low-frequency adaptation of the phased array system.

References

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2. G. Maes, Mathematical model for the development and optimization of ultrasonic transducers for non-destructive testing in the nuclear industry. MATHEMATICAL and INTELLIGENT models in system simulation: JC Baltzer AG, Scientific Publishing Co IMACS, 1991, pp. 403-408 [magazine article]

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4. Gebhardt W.G., *Electronic Beam Forming, Defect Reconstruction and Classification by Ultrasonic Phased Arrays.* NON DESTRUCTIVE TESTING, Vol, 7, 1984, pp. 115-143. [book]

5. "EPRI Phased Array Inspection Seminar ". Portland August/September 1998. [seminar proceedings]

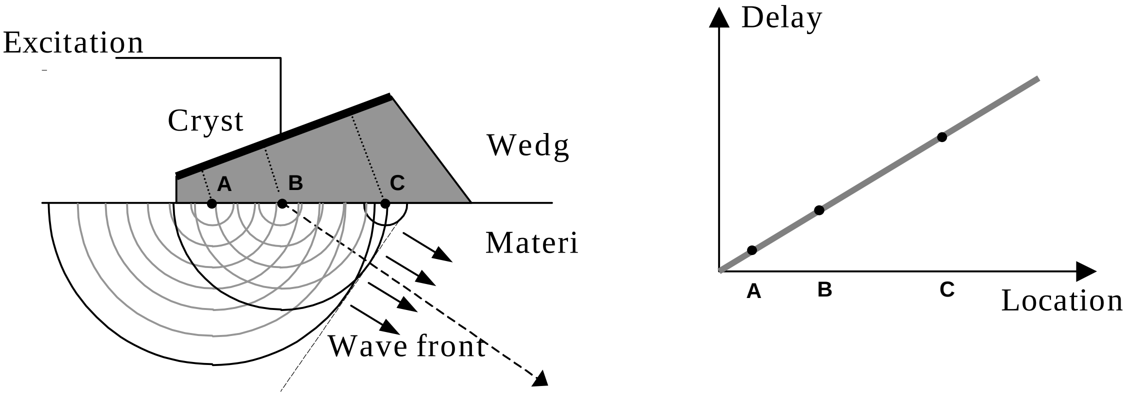


Fig 1a:The wave generated by the crystal arrives at different time intervals at the interface due to delays introduced by the wedge. Each point at the interface can be considered as a new punctual source emitting a spherical wave. The generated wave at location A starts traveling first into the material, then B, then C. The line represents

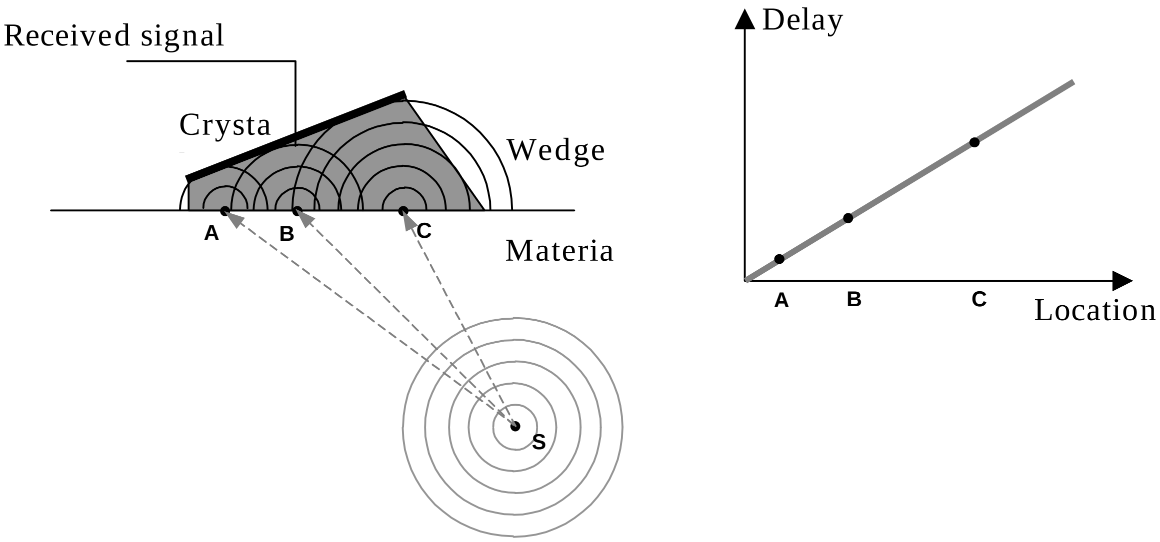


Figure 1b: Received wave in case of conventional probe

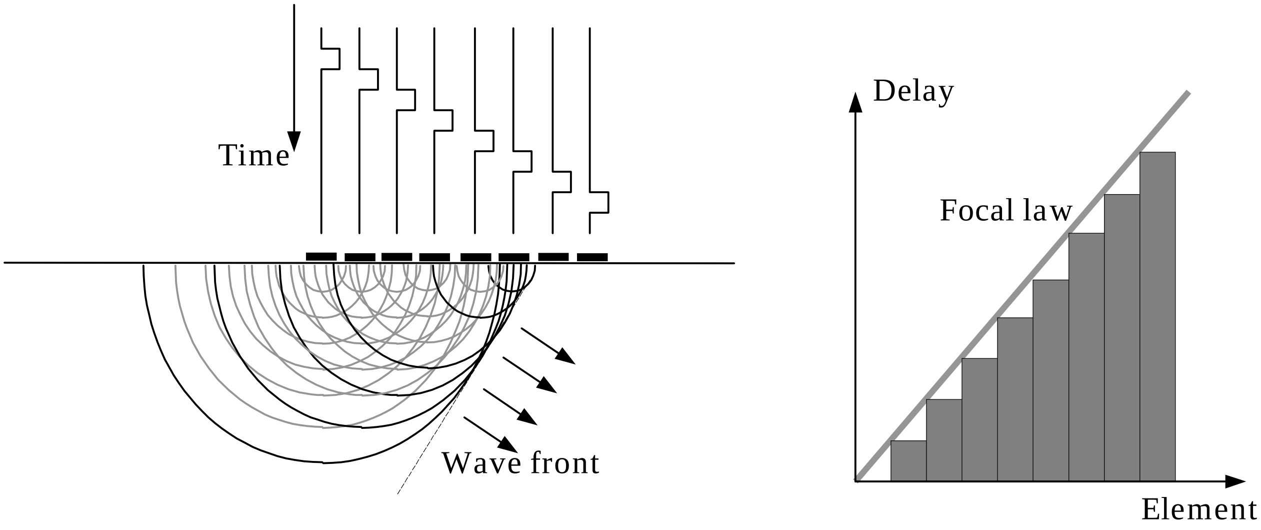


Figure 1c: Phased Array probe, emission

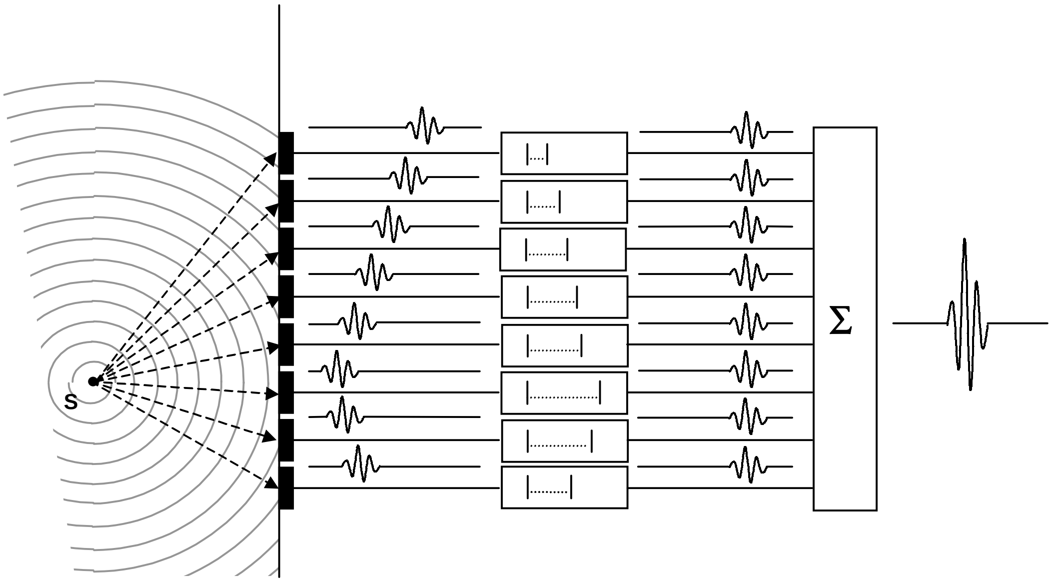


Figure 1d: Phased array probe, delays at reception

Figure 1 Principle of the phased array technique

TRL PROBE

TRANSMITTER RECEIVER L WAVES PROBE

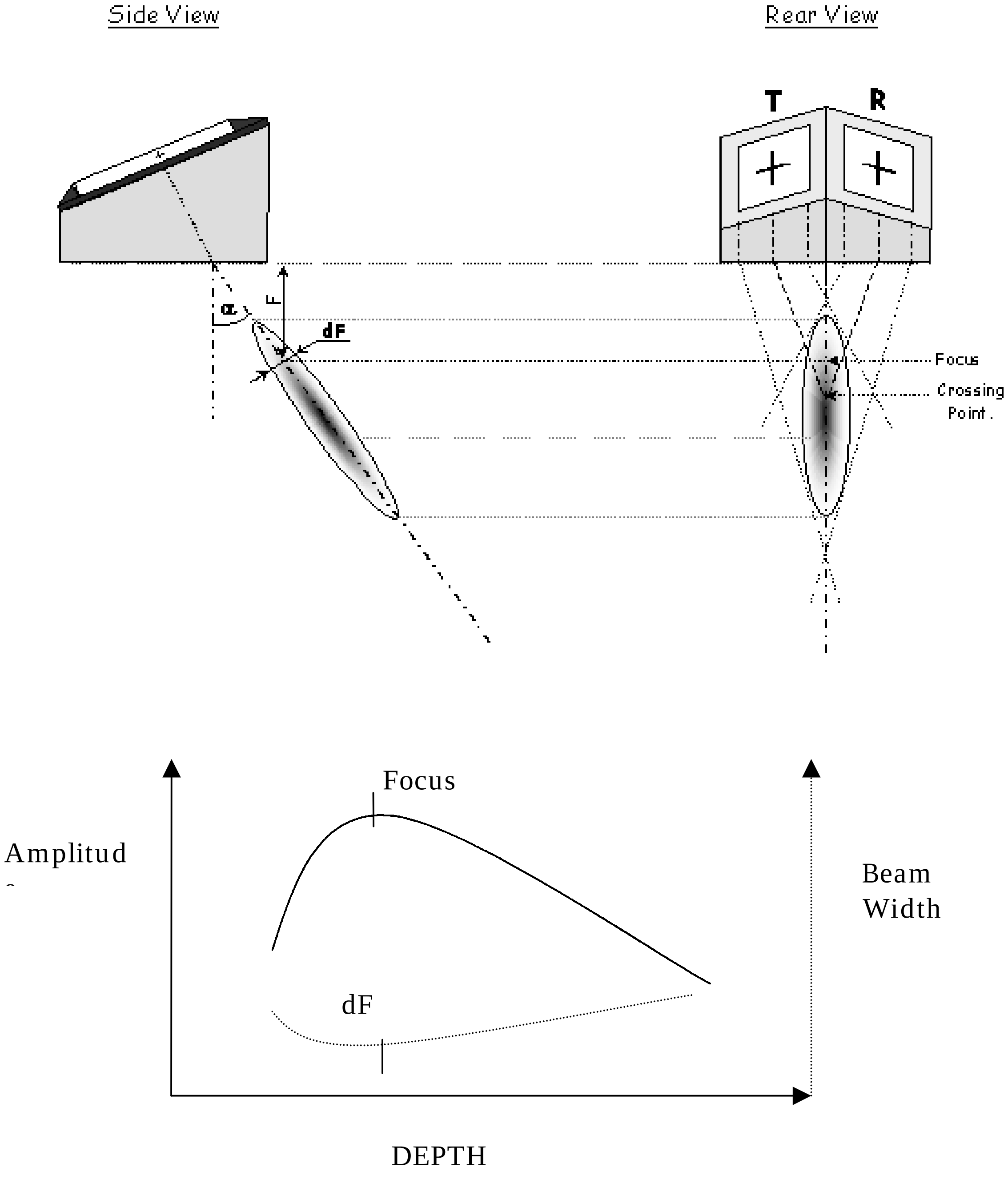


Figure 2. TRL Probe

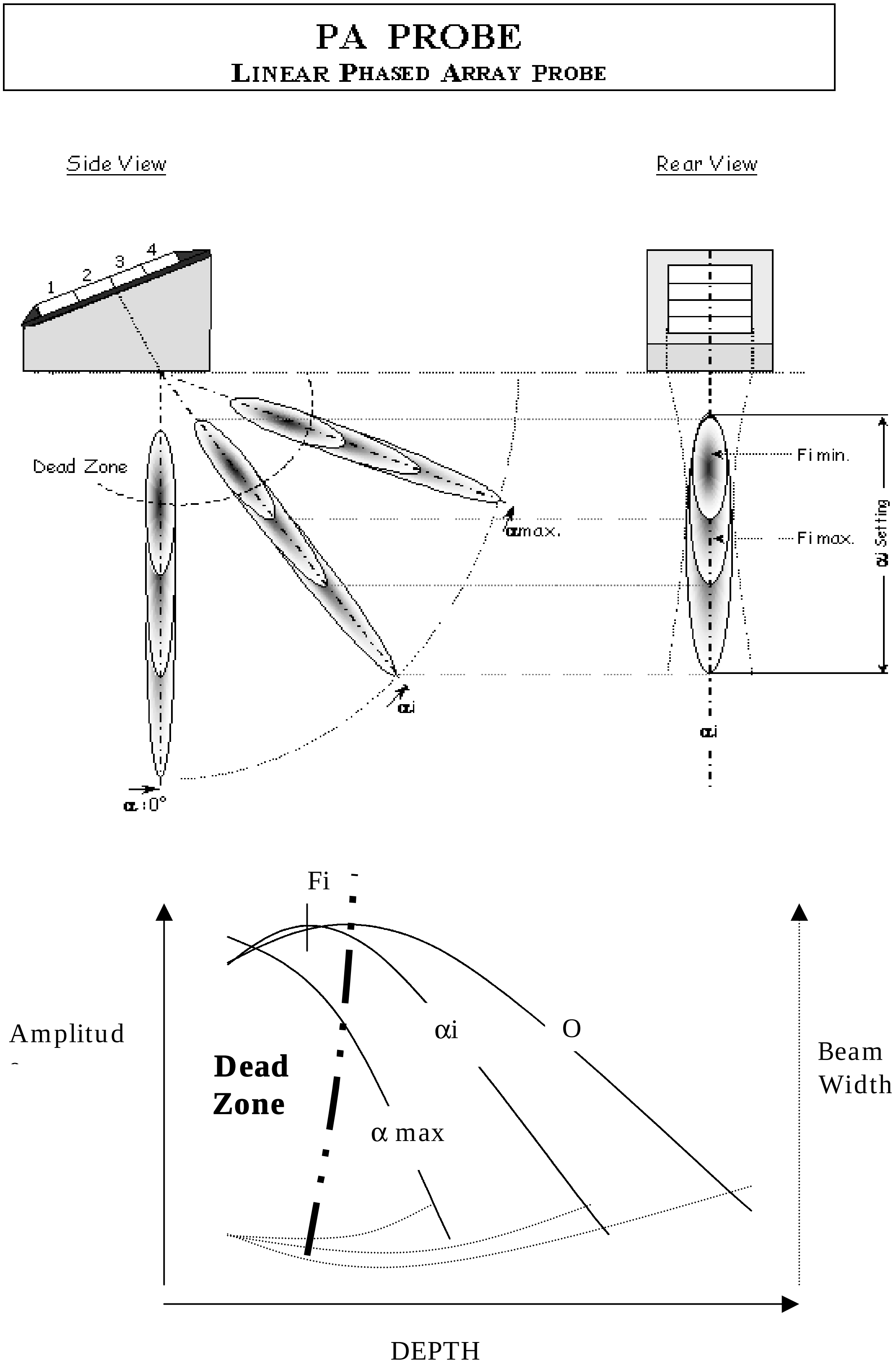


Figure 3. PA Probe

TRL PA PROBE
TRANSMITTER RECEIVER L WAVES PHASED ARRAY PROBE

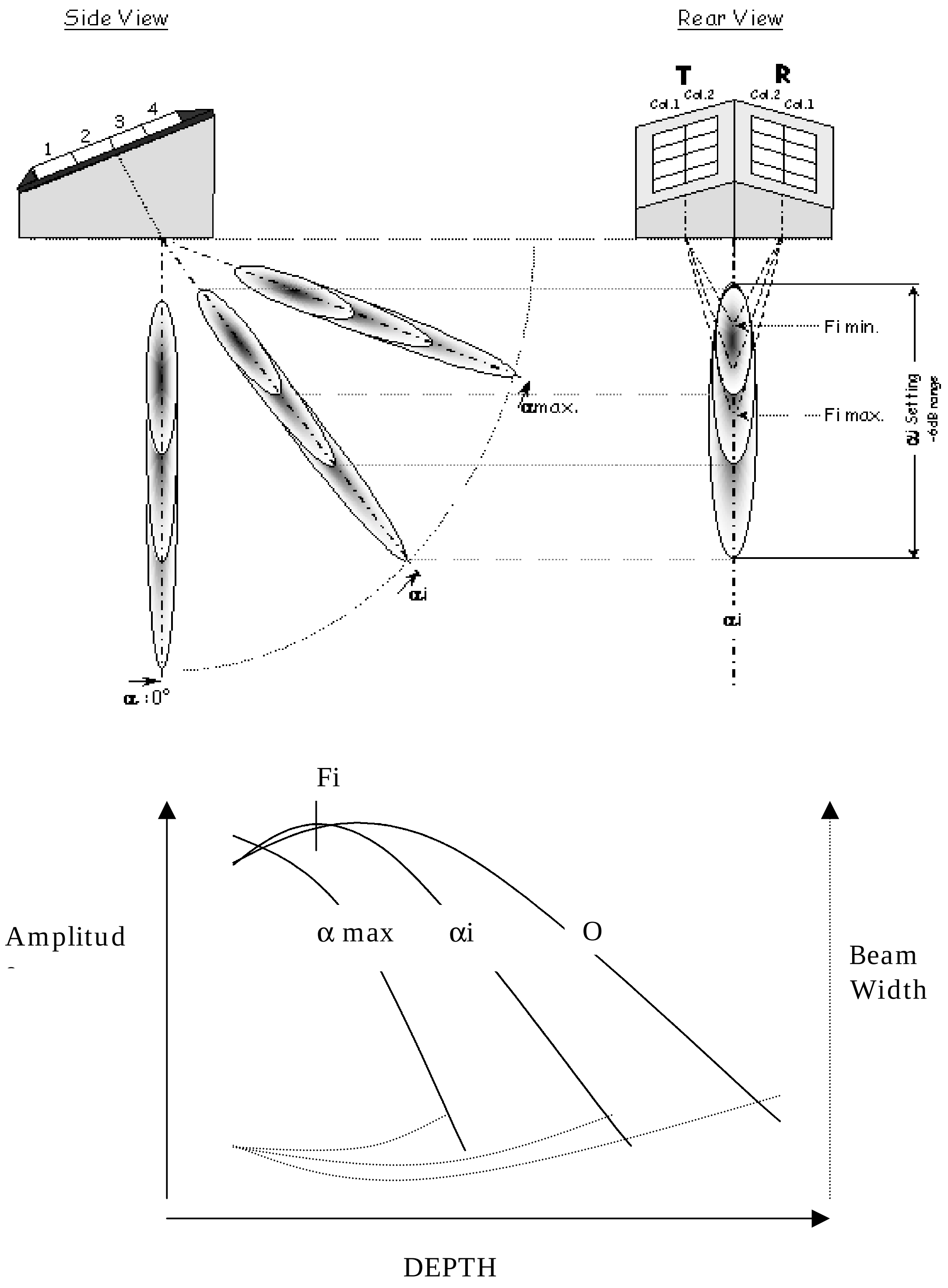
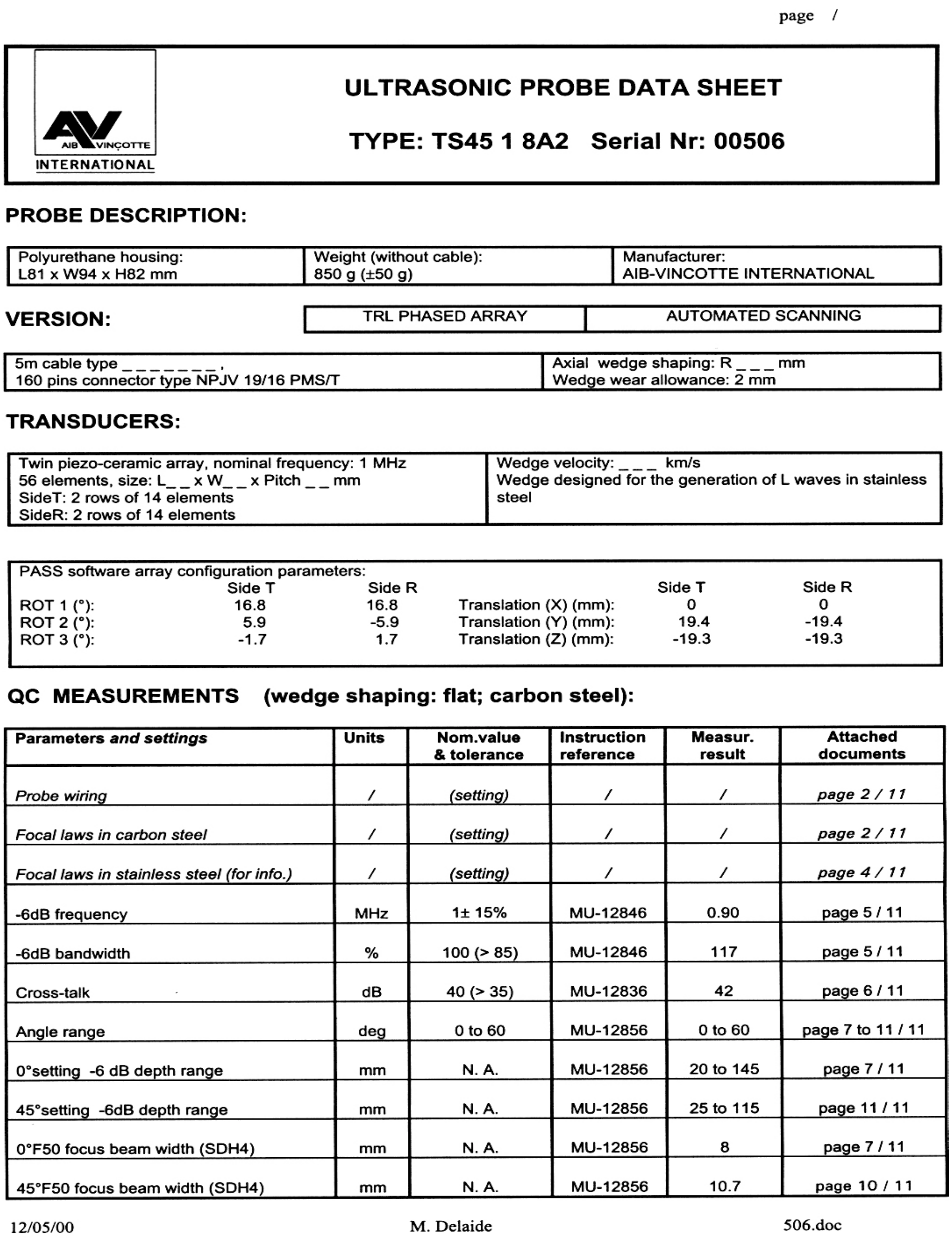


Figure 4. TRL PA Probe

TS45 1 6A1: General View

TS45 1 6A1: View of the Wedges

Figure 5 TRL PA probes



page /

AIB VINÇOTTE INTERNATIONAL

ULTRASONIC PROBE DATA SHEET

TYPE: TS45 1 8A2 Serial Nr: 00506

PROBE DESCRIPTION:

Polyurethane housing: L81 x W94 x H82 mm	Weight (without cable): 850 g (±50 g)	Manufacturer: AIB-VINCOTTE INTERNATIONAL

VERSION:

TRL PHASED ARRAY	AUTOMATED SCANNING

5m cable type _ _ _ _ _ _ _ _ , 160 pins connector type NPJV 19/16 PMS/T	Axial wedge shaping: R _ _ _ mm Wedge wear allowance: 2 mm

TRANSDUCERS:

Twin piezo-ceramic array, nominal frequency: 1 MHz 56 elements, size: L_ _ x W_ _ x Pitch _ _ mm SideT: 2 rows of 14 elements SideR: 2 rows of 14 elements	Wedge velocity: _ _ _ km/s Wedge designed for the generation of L waves in stainless steel

PASS software array configuration parameters:

	Side T	Side R		Side T	Side R
ROT 1 (°):	16.8	16.8	Translation (X) (mm):	0	0
ROT 2 (°):	5.9	-5.9	Translation (Y) (mm):	19.4	-19.4
ROT 3 (°):	-1.7	1.7	Translation (Z) (mm):	-19.3	-19.3

QC MEASUREMENTS (wedge shaping: flat; carbon steel):

Parameters *and settings*	**Units**	**Nom.value & tolerance**	**Instruction reference**	**Measur. result**	**Attached documents**
Probe wiring	/	*(setting)*	/	/	*page 2 / 11*
Focal laws in carbon steel	/	*(setting)*	/	/	*page 2 / 11*
Focal laws in stainless steel (for info.)	/	*(setting)*	/	/	*page 4 / 11*
-6dB frequency	MHz	1± 15%	MU-12846	0.90	page 5 / 11
-6dB bandwidth	%	100 (> 85)	MU-12846	117	page 5 / 11
Cross-talk	dB	40 (> 35)	MU-12836	42	page 6 / 11
Angle range	deg	0 to 60	MU-12856	0 to 60	page 7 to 11 / 11
0°setting -6 dB depth range	mm	N. A.	MU-12856	20 to 145	page 7 / 11
45°setting -6dB depth range	mm	N. A.	MU-12856	25 to 115	page 11 / 11
0°F50 focus beam width (SDH4)	mm	N. A.	MU-12856	8	page 7 / 11
45°F50 focus beam width (SDH4)	mm	N. A.	MU-12856	10.7	page 10 / 11

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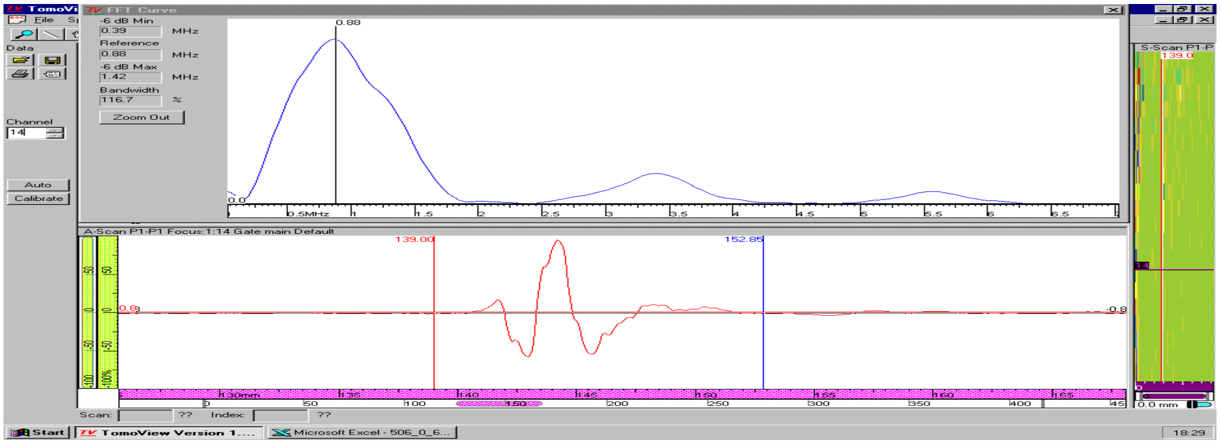
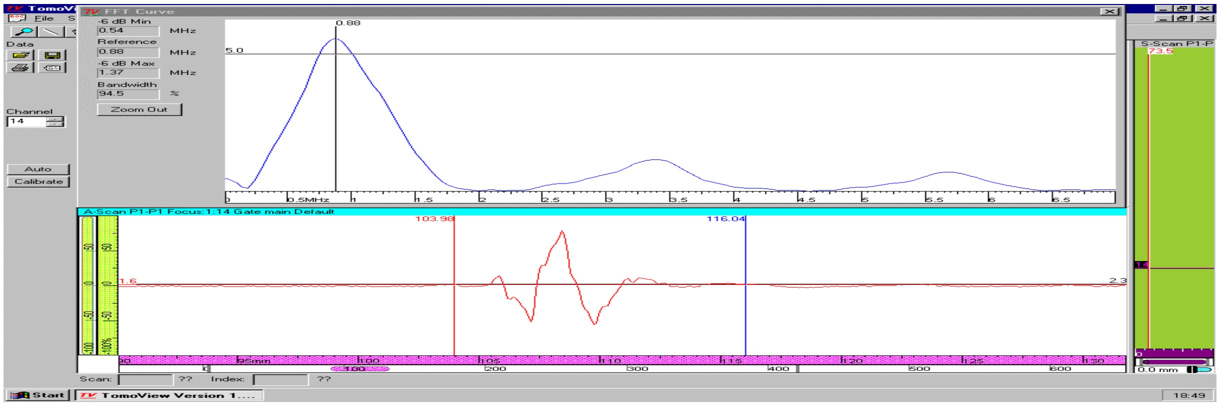
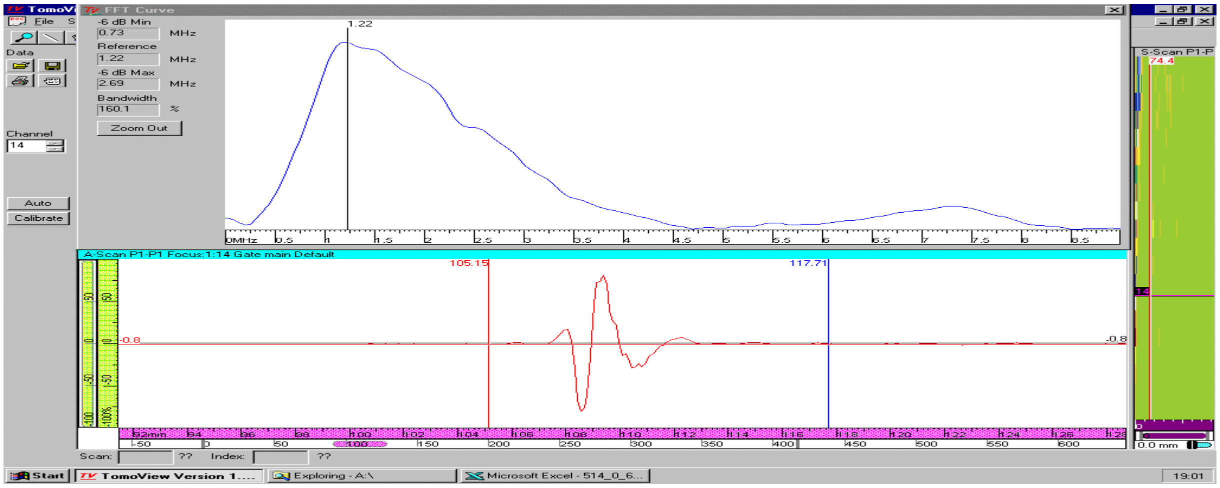
Figure 6 Example of a TRL PA probe Data Sheet


-6 dB Min 0.39 MHz
Reference 0.88 MHz
-6 dB Max 1.42 MHz
Bandwidth 116.7 %
Channel 14

TS45 1 8A2 SN 00506 Central frequency 0.88 MHz; Bandwidth 117%


-6 dB Min 0.54 MHz
Reference 0.88 MHz
-6 dB Max 1.37 MHz
Bandwidth 94.5 %
Channel 14

TS45 1 6A1 SN 00514 Central frequency 0.88 MHz; Bandwidth 95%


-6 dB Min 0.73 MHz
Reference 1.22 MHz
-6 dB Max 2.69 MHz
Bandwidth 160.1 %
Channel 14

TS45 2 6A1 SN 00505 Central frequency 1.22 MHz; Bandwidth 160%

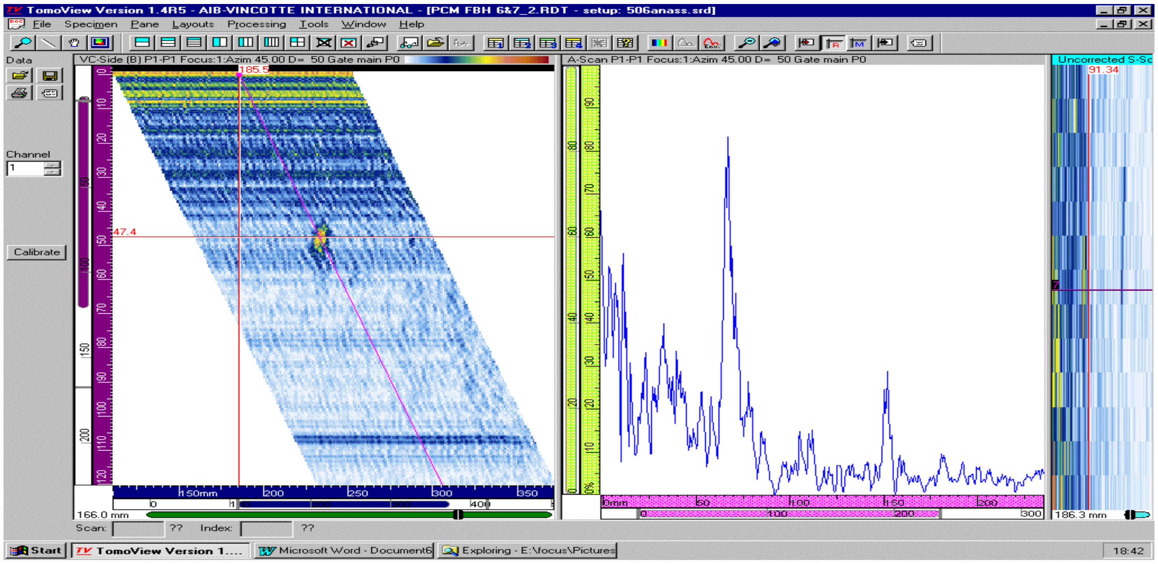
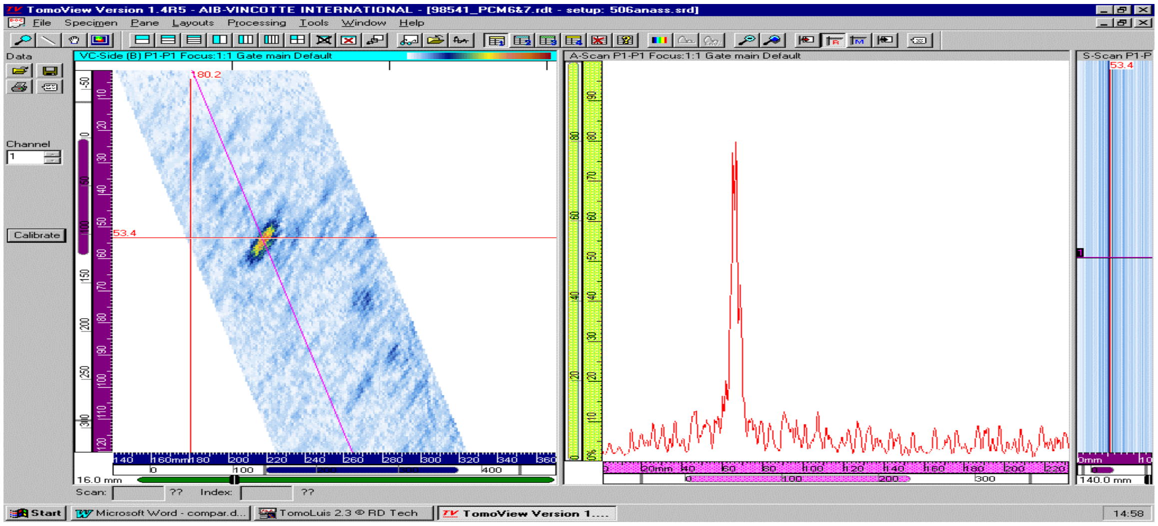
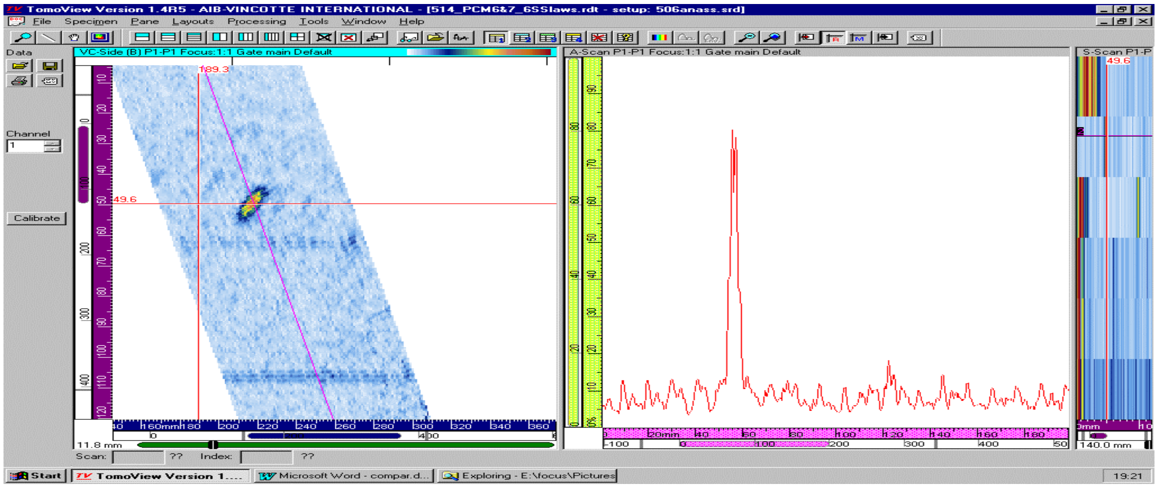


Figure 7. RF Signals and Bandwidth of TRL PA

PA probe 1L16E60 30 SN 001

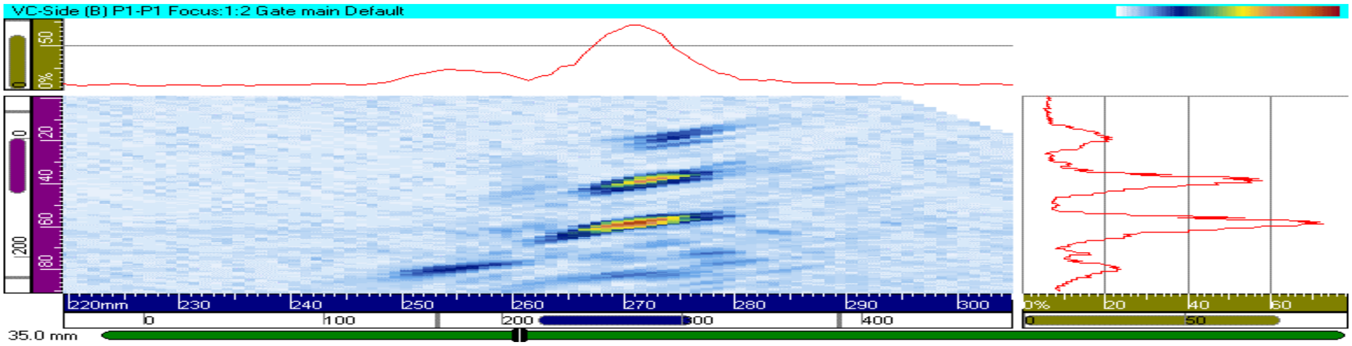


TRL probe TS45 1 635 SN 98666

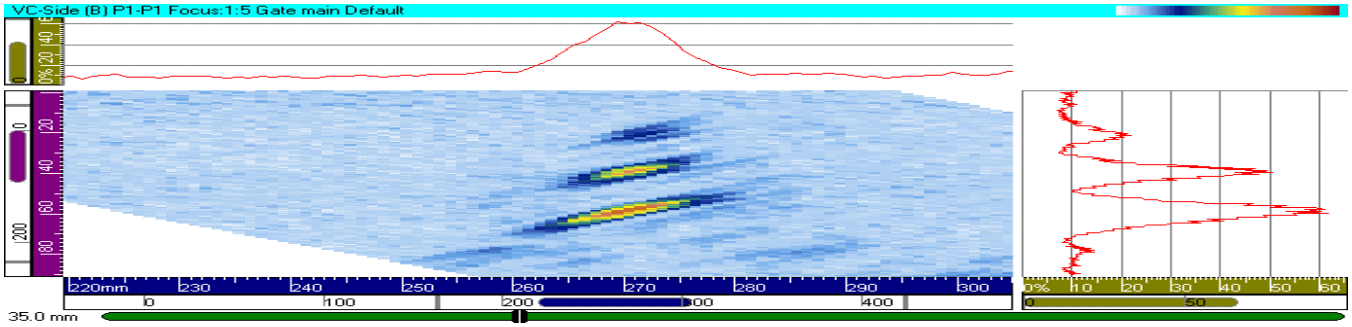


TRL PA probe TS45 1 6A1   SN 514

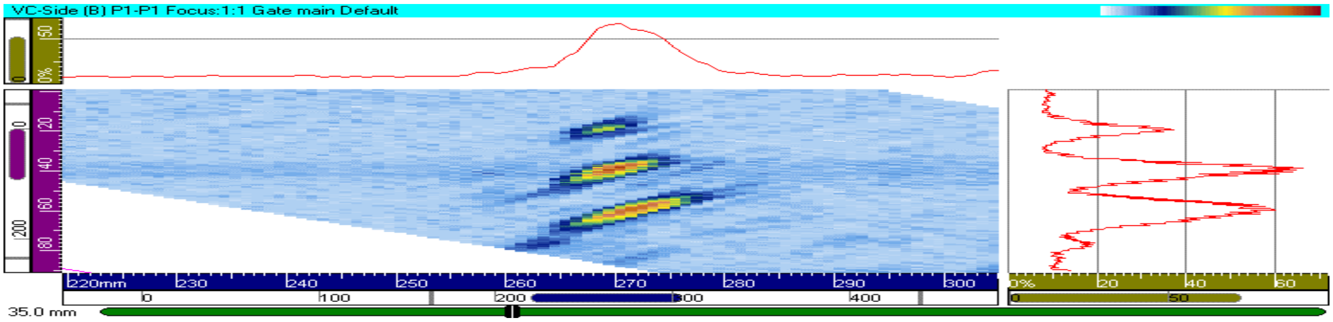
Figure 8 Comparison between PA, TRL and TRL PA on FBH7 Depth 50 mm



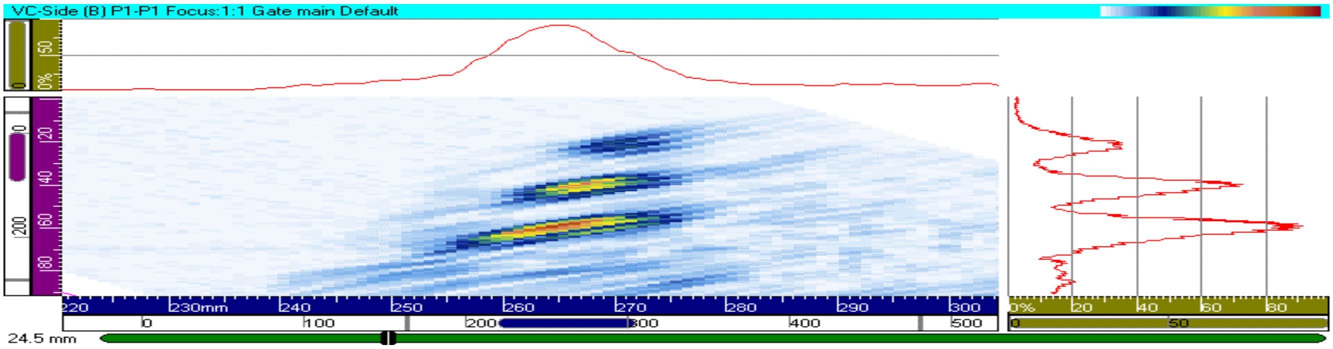
TRL PA probe TS45 1 6A1   SN 514, Settings: 30° focal depth 50 mm



TRL PA probe TS45 1 6A1   SN 514, Settings: 45° focal depth 75 mm



TRL PA probe TS45 1 6A1   SN 514, Settings: 50° focal depth 50 mm



Focused TRL TS45 1 635   SN 98666

Figure 9 Comparison between TRL PA and TRL on SDH4.8 depth 20, 40, 60 mm

FOCUS SYSTEM

Figure 10

Table 1: UT PROBES

Type	Nominal Frequency (MHz)	Casing Dimensions (L x W x H) (mm)	Elements Configuration	Manufacturer
TS45 2 6A1 (TRL PA)	2	62 x 77 x 70	64 elements (4 col. of 16 el.)	AIB-Vincotte International
TS45 1 6A1 (TRL PA)	1	62 x 77 x 70	44 elements (4 col. of 11 el.)	AIB-Vincotte International
TS45 1 8A2 (TRL PA)	1	81 x 94 x 82	56 elements (4 col. of 14 el.)	AIB-Vincotte International
TS45 1 635 (focused TRL)	1	60 x 60 x 35	2 elements (transmitter and receiver)	AIB-Vincotte International
1L16E60.30 (PA) (removable wedge)	1	65 x 35 x 35	16 elements (1 col. of 16 el.)	Vermon

Table 2: Measurements on the PCM Block

Probe	**SDH5 D50**		**FBH7 D50**		
	Beam Width (inc. plane) (mm)	**S/N (dB)**	**Beam Width (inc. plane) (mm)**	**Beam Width (perp. plane) (mm)**	**S/N (dB)**
TS45 1 8A2 SN 506	12	19	14	19	13
TS45 1 6A1 SN 514	12	15	13	16	16
TS45 1 635 SN 98666	15	16	13	17	16
1L16E60 30 SN 001	16	6	12	18	8