MODIFIED PHASED ARRAY CONCEPT FOR AUT OF LNG STORAGE TANKS

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ABSTRACT

Natural Gas, in order to be liquefied, needs a low temperature and is stored under cryogenic conditions. Typical storage temperature is below -160° Centigrade. Apart from the fact that this requires the tanks to be fitted with effective thermal insulation and cooling equipment, the tank shell is made out of a steel alloy containing 9% Nickel in order to remain ductile at low temperatures; where typical wall thicknesses vary between 10 mm (top rings) and 30 mm (bottom ring).

In recent years, a tendency can be observed to switch, for NDT of the welds, from Radiography to Automated Ultrasonic Testing (AUT). Not only does this increase inspection speed and detection capabilities of critical defects; but thanks to the absence of radiation, the AUT activities can also be performed in the vicinity of personnel at work, enabling continuous welding and instant NDT results. Since welding is done with high-alloyed welding consumables, resulting in the weld structure to be anisotropic and coarse grained, ultrasonic techniques using angled longitudinal waves should be used. These techniques include longitudinal beams under 45° to 70°, creeping waves and Round Trip Tandem technique (RTT, also referred to as Self Tandem Technique).

If performed with conventional dual element Transmitter Receiver Longitudinal (TRL) probes, a typical probe arrangement contains 6 to 10 probes. Their indices have different distances to the weld centre line, to optimize for the different parts of the weld. In addition, a probe arrangement similar to Time of Flight Diffraction (ToFD) is used to detect possible root defects, but using reflection rather than diffraction signals. Inspection is usually done in accordance with API 620, 11th edition, February 2008.

Dual phased array probes used to mimic the functions of TRL probes are commercially available. However, these have only limited abilities to steer the beam in lateral direction to correct for different focal depths, and they have only one fixed index for all beams (index cannot be shifted to optimize for zones). This paper will discuss a novel, simple dual phased array design, allowing a weld scan plan that is very similar to TRL probes. This includes the possibility of using creeping wave and flexible tandem techniques, without the need of an excessive amount of elements. This probe design does not need lateral beam steering to be effective in all zones. Its capabilities for detection and sizing, in accordance with the Code’s requirements and acceptance criteria (table U1 and U2) will be discussed.

INTRODUCTION

The number of installations for liquefaction of Natural Gas and storage of the liquefied product (LNG) is rapidly increasing worldwide. Although the financial crisis certainly impacts the LNG market, long-term LNG development projects are less affected. As a result, a significant number of LNG installations are under construction, each including facilities for LNG storage (see fig. 1).

Fig. 1: LNG storage tank under construction

Liquefaction of Natural Gas is only possible at temperatures below -160°C. This implies that storage has to take place under cryogenic conditions as well. Therefore the bottoms, walls and roofs of LNG storage tanks need to be thermally insulated. Usually, these tanks have a steel inner shell, forming the actual containment of the fluid, and an outer (concrete) shell. Between the inner and outer shells, a thick layer of thermal insulation material is present. The inner shell is constructed out of steel plates welded horizontally and vertically, with typical dimensions (LxH) of 12 x 3 metres. These plates should remain ductile at cryogenic temperatures and hence usually an alloy containing 9% Nickel is used. Welding requires high-alloy welding consumables as well. As a result, welds in LNG storage tanks usually have an anisotropic and coarse-grained structure.

Traditionally, NDT of the horizontal and vertical welds is performed with industrial radiography. Nowadays, automated ultrasonic techniques are used ever more to replace radiography, for several reasons.

THE NATURE OF WELDS IN LNG STORAGE TANKS

Wall thicknesses of LNG tank inner shell vary between typically 25 mm to 30 mm (bottom ring) and 10 mm (top rings). The wall thickness differences between subsequent rings are typically 3 mm.

Vertical welds usually have a symmetrical shape, horizontal welds an asymmetrical shape (see Fig. 2). Welds are often made by starting with a V shape weld from one side, usually the outside, followed by manual back chipping at the opposite side. This leads to an X-shape weld, whereby the bevel shape at the inside is less well defined than the one at the outside.

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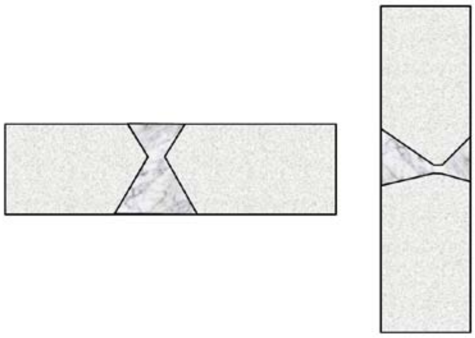

Fig. 2: Schematics of typical horizontal and vertical welds

CONVENTIONAL ULTRASONIC TECHNIQUES FOR UT OF AUSTENITIC WELDS

Around 1968, it was first discovered that longitudinal waves rather than shear waves needed to be used for ultrasonic testing of austenitic stainless steel weld material. This eventually led to a series of joint development programs between Applus RTD and Bundesanstalt für Materialprüfung (BAM).

This work included the development of TRL probes for inspection of clad material (1972) and austenitic stainless steel welds (1974). At that time, only direct defect detection was believed to be possible because the use of longitudinal waves for detection over skip proved to be complex (too much energy is lost because of wave mode conversion on the back wall). As a result, the weld cap had to be ground flush in order to be able to detect defects near the scanning surface.

In the following years, Applus RTD and BAM discovered how over-skip techniques such as the RTT technique could be used for enhanced defect detection. In addition, BAM developed the Creeping Wave technique. This technique made it possible to inspect austenitic welds without flush grinding the cap. Secondary creeping waves (generated by the shear waves, or so-called “head waves”) are even capable of detecting surface flaws at the opposite surface. Fig. 3 shows the wave modes emitted by a TRL probe including reflection and wave mode conversion on the back wall (creeping waves have been omitted in this sketch).

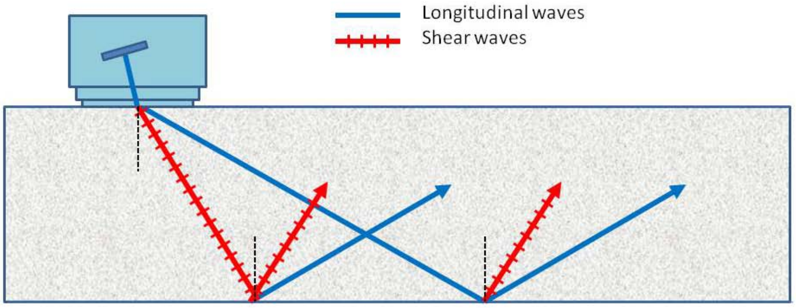

Fig. 3: Wave modes of longitudinal angle probes

Nowadays, austenitic stainless steel welds, together with other coarse-grained anisotropic welds, are ultrasonically tested with these techniques all over the world. A useful IIW Handbook on UT of austenitic stainless steel welds (first issued in 1986), recently saw its second edition [1]. A new European standardization for UT of austenitic stainless steel welds is currently under development.

It is known that TRL probes are only suitable for the inspection of defined layers (zones) in the material. This is because separate transmitter and receiver elements are used, whereby the beams intersect at a defined depth. As a consequence, each depth zone requires appropriate probe settings, e.g. the squint angle of the elements (see figs. 4 and 5). Therefore, the use of TRL concept usually requires that the wall thickness is divided into zones, and a separate probe is used on each zone. The combination of TRL probes should be designed in such a way that full through-thickness coverage is achieved. This makes the inspection more complex than during inspections using single element probes. Nevertheless, dual element probes are widely used, for the following reasons.

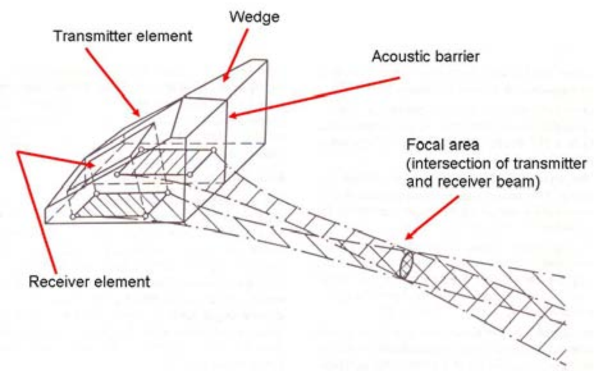

Fig. 4: Configuration of a TRL probe

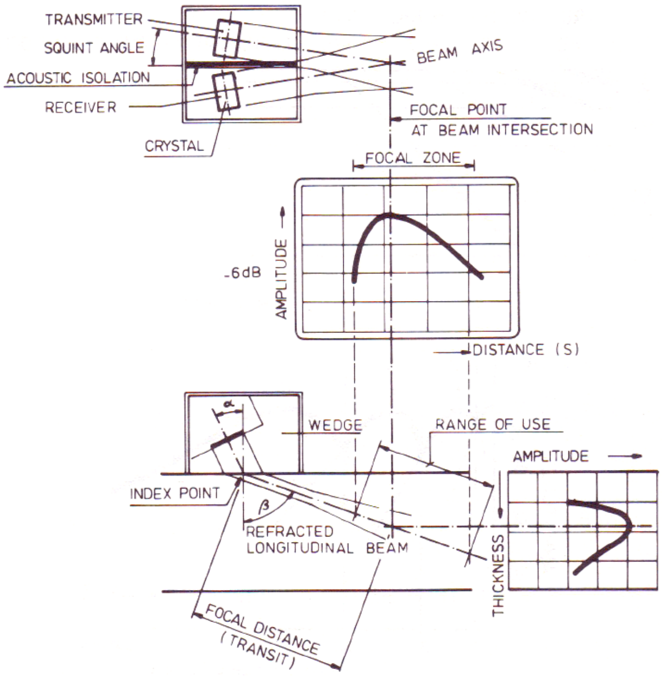

Fig. 5: Sensitivity diagrams of a TRL probe

One important reason is that TRL probes do not suffer from internal reflections from the wedge. In single element probes these are much more difficult to suppress, especially in longitudinal angle probes because of their smaller wedge angle. Fig. 6 shows how the angles differ for longitudinal and shear beams. The green arrows illustrate possible paths of reflection in the wedges. As a consequence, dual element probes are especially useful when short ranges are at stake (creeping waves, near surface flaws, thin walls and for inspection of austenitic stainless steel cladding).

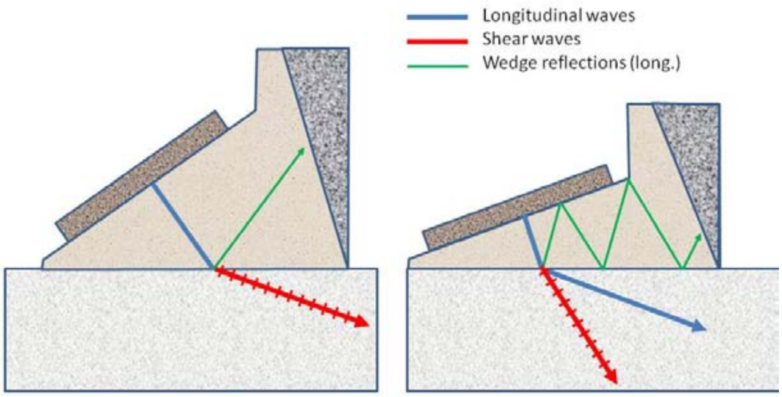

Fig. 6: Wedges for 70° shear waves (left) and 70° longitudinal waves (right) in steel (Perspex wedge)

But there is another reason to use dual element rather than single element probes: dual element probes can offer a better signal to noise ratio [1]. This can partly be explained by the fact that the transmitted and received energy do not follow the same path; as a consequence, wave propagation is (on transmission and reception) affected by different grains, which can have a favorable effect on the signal, similar to spatial averaging (noise reduction). Another part of the explanation is the fact that, using TRL probes, the material volume from which scattering is received is smaller than in case of single element probes (quasi focusing effect).

Despite the advantages of TRL probes, single element longitudinal angle probes are also used, for instance for less critical applications or in those cases where short ranges are not applicable.

USE OF PHASED ARRAYS FOR UT OF AUSTENITIC STAINLESS STEEL

Phased array technology for ultrasonic testing of austenitic stainless steel welds is readily available in the market. The simplest solution is to use a single array on a single wedge, whereby the wedge angle is chosen to correspond with an average angle of longitudinal waves rather than shear waves in steel. This leads to a wedge angle of typically 20 to 22° (Perspex), whereas the wedge angle for shear waves would be between 35 and 40°. If the wedge manufacturer takes good care of the necessary suppression of spurious reflections from the wedge, such an approach can be used for applications where signal to noise ratio is not of utmost importance. An obvious advantage of the use of a single array is the fact that the weld does not need to be divided in zones, because the probe does not have a distinct focal distance. As a result, advantage can be taken of the use of sectorial scans.

Fig. 7 shows an example of an array on a wedge for longitudinal waves. The wedge angle is approx. 20°. The array in the given example has sufficient length to move the probe index, thus allowing for multiple sectorial scans with various indices. This enhances detection of planar defects, because there is an increased chance that expected defect orientations are hit perpendicularly. It even enables the use of (round trip) tandem technique at different depths (when different parts of the array are used for transmission and reception). It should be noted that when using longitudinal waves, shear waves are inevitably generated, which can lead to misinterpretations if not properly dealt with.

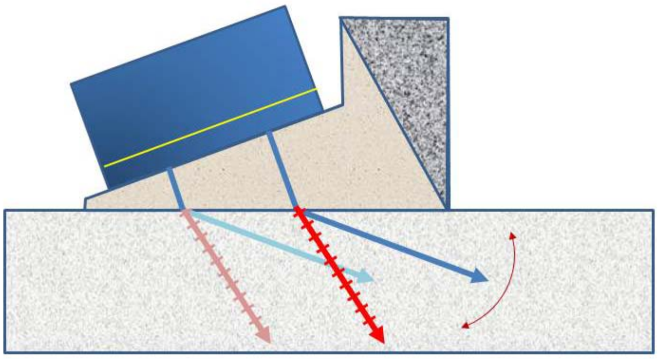

Fig. 7: Elongated single phased array on wedge for longitudinal waves

Another possible solution available on the market is a dual wedge for longitudinal waves, where both halves of the wedge are equipped with a phased array. In this way, a conventional TRL probe with variable angle can be mimicked. In order to adapt the roof angle to each depth zone individually, so called 1½D arrays are often used (see Fig. 8), which can be considered as matrix arrays (normally referred to as 2D arrays) but with limited lateral steering capabilities. Such arrays are suitable for single-index sectorial scans because of limited array length.

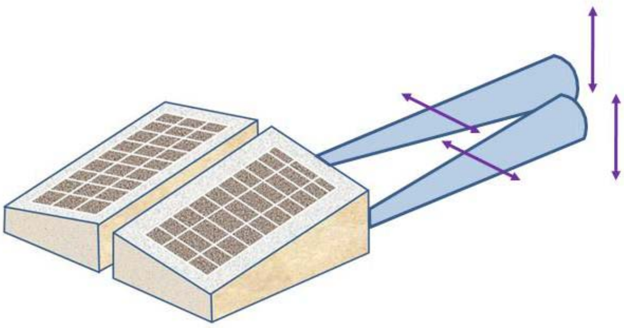

Fig. 8: Example of an 1½D dual phased array, allowing vertical and (limited) horizontal beam steering

Whether single or dual wedge phased arrays are used, care should be taken in interpretation of the scan results. This is because different detection modes exist such as direct, indirect through a longitudinal-longitudinal wave path (L-L), indirect through a shear-longitudinal path (S-L, with wave mode conversion on the back wall), and L-L-S or RTT, see Fig. 9 (Note that indirect mode L-L is very inefficient, due to energy losses in mode conversion).

If one of these modes is used, it should be kept in mind that one or more of the others (if suitable reflectors are present, such as geometry) will still generate signals. These can only be distinguished from relevant signals by their transit distance. In order to use these techniques to their full advantage and to avoid misinterpretations (missed defects or false calls), operators should receive specialized training on these techniques.

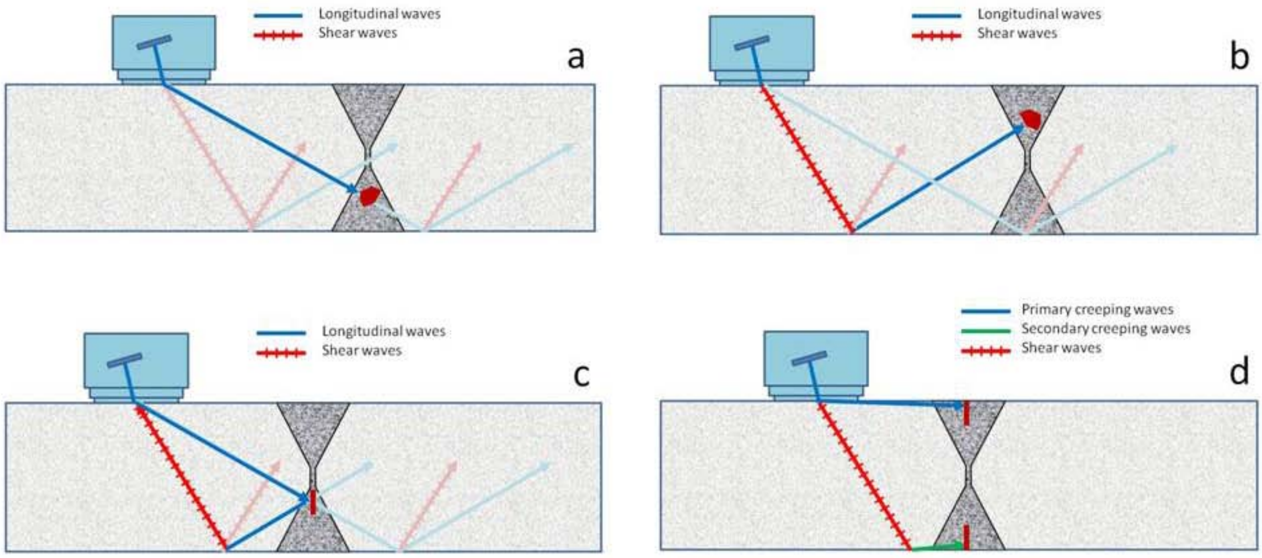

Fig. 9: Different detection modes: Direct detection (a), indirect S-L (b), L-L-S or RTT(c), creeping waves (d)

NDT OF WELDS IN LNG STORAGE TANKS

Radiography

Traditionally, welds in LNG storage tanks have been radiographically tested for many years. It is known that the use of this NDT method has some serious drawbacks. From a logistics point of view, it is required that the test area is cleared from all personnel, including welding crew. This causes interruptions of the work flow and prevents that NDT results are known at an early stage, making corrective actions less efficient (in e.g. settings of welding equipment). From a technical point of view, it is known that radiographic images taken on austenitic stainless steel and Inconel welds can be blurred and can contain ghost images because of scattering and diffraction on columnar grains. These phenomena can lead to missed defects and false calls.

Automated Ultrasonic Testing (AUT) using TRL probes

In 1980 a feasibility study conducted by Applus RTD for a Japanese client demonstrated for the first time that welds in LNG storage tanks could be ultrasonically tested with TRL probes. In that period, it was deemed important to detect (alongside defects on the bevel) cold cracks on the weld center line, which had led to weld failure in some LNG tanks. This was the reason that the RTT technique was introduced in a research program conducted by Applus RTD together with a major client. Nevertheless, it took almost twenty years until ultrasonic testing of welds in LNG tanks was introduced at a commercial scale. One of the main factors for this delay was the development of codes. Nowadays, a major storage tank Code such as the API 620 allows for the use of ultrasonic techniques in lieu of radiography [2].

Current conventional multi probe systems include TRL probes which are used for direct detection as well as RTT. Additionally, creeping wave probes (TRL probes with 90° longitudinal waves and an optimized crystal arrangement) are also utilized. Such probe systems are sometimes supplemented with shear wave probes, allowing for detection of lack of fusion defects on the fusion line over skip. The latter technique takes advantage of the fact that (in case of LNG storage tanks) only the weld metal poses difficulty for wave propagation, not the parent metal.

In addition to these probes, Applus RTD has introduced a pair of single element longitudinal angle probes, positioned at either side of the weld, together forming an arrangement similar to ToFD technique. However, the purpose of these probes is not to perform defect detection using ToFD, as it is known that signal to noise ratio is generally too poor to receive diffraction signals from defect edges in coarse grained, anisotropic welds. These probes are used to enable detection of reflected signals from the opposite surface, e.g. in the presence of defects like hollow beads. These can often be detected because they are usually stronger than diffraction signals, and can support defect sizing once a defect is detected. To enhance signal to noise ratio, the crystals are made larger than in case of ToFD to restrict beam spread, which is possible since the entire wall thickness does not require full coverage with this single technique. The fact that reflections are detected rather than diffractions has given this technique its name: ToFR, or Time of Flight Reflection technique(see Fig. 10).

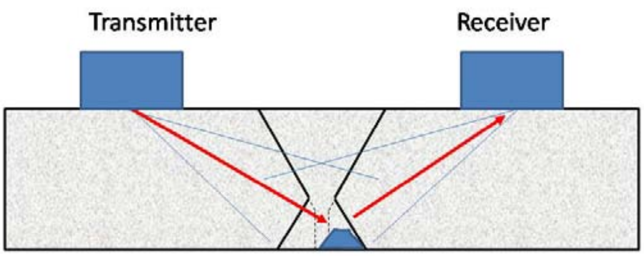

Fig. 10: Time of Flight Reflection (ToFR) technique

A typical example of a complete multi-probe arrangement is depicted in Fig. 11, where all ultrasonic beams are chosen in such a way that potential planar defect are hit perpendicularly. This enables the use of echo amplitude for defect height sizing.

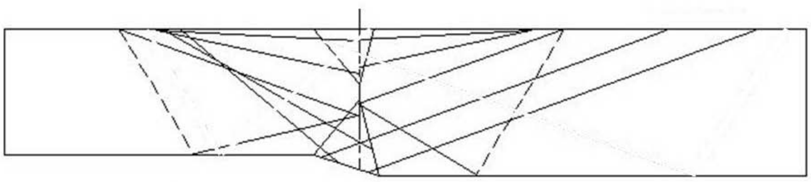

Fig. 11: Conventional multi TRL probe arrangement for LNG storage tank NDT

Phased arrays

For the testing of welds in LNG tanks, two different phased array techniques are on the market.

One of these techniques uses a single array on a single wedge at either side of the weld. The longitudinal beam is steered between e.g. 40° and 80°, thus covering the entire weld volume with longitudinal waves and (near) creeping waves. A conventional sectorial scan display can be used. This technique is usually applied in direct incidence of possible defects: if additional techniques such as RTT are used, interpretation of the sectorial images will be complex. Unless multiple sectorial scans are made (which requires an array with a certain length), the index point will be a compromise whereby the fusion line is not necessarily hit perpendicularly. This means that, in order to be able to size defects, one has to rely on diffraction signals from the edges of defects which are not always available due to the weld metal structure.

The second technique uses a dual wedge in an 1½D arrangement, as presented in Fig. 8. This arrangement takes advantage of the higher signal to noise ratio of the TRL technique. Also in this case, sectorial scans can be made whereby lateral beam steering of the probe halves is used to adapt the beams intersections to different depths. This technique has the same sizing limitations as the previous one. Since potential defects are not hit perpendicularly, signal amplitude cannot be used as a sizing mechanism.

LEGISLATION

The applicable code is, in most cases, API 620 [2]. This code allows for the use of AUT in lieu of radiography (subject to performance demonstration) and acknowledges the difficulties in defect height sizing that can arise in case of austenitic welds. Therefore, it gives two options for weld defect acceptance criteria in appendix U:

1. Table U1 (may be used on all materials) poses a maximum acceptable flaw length as a function of height, separately for surface and subsurface (embedded) flaws. This requires that the ultrasonic technique has some means of assessing flaw height. This may be achieved by the primary detection technique, but also by a separate (manual) sizing technique to be specified in the procedure.

2. Table U2 (may only be used if certain toughness criteria are met) gives a maximum limit on flaw length, separately for surface and subsurface (embedded) flaws. This requires less accurate height sizing. Flaw assessment for acceptance or rejection may be performed with the primary detection technique or by a separate (manual) technique, to be specified in the procedure.

HOW EXISTING UT TECHNIQUES COMPLY WITH API CODE REQUIREMENTS

Although usually adequate for detection, single-index phased array techniques (single wedge or 1½D dual wedge) are not always able to provide defect sizing capabilities required for flaw assessment in the sense of table U1 or U2 of API 620, because diffraction signals from defect edges are not always available. Although manual sizing techniques are allowed, they require precious inspection time, depending on the number of indications found.

The conventional TRL multi probe concept however, is designed in such a way that potential flaws at the fusion line are hit perpendicularly, which is a prerequisite for amplitude sizing. This sizing technique is inspired by pipeline AUT, and has proven to be more than accurate enough for sizing in austenitic welds. In this way, both table U1 and U2 can be used (which one is to be used is always subject to agreement with the Client). In order to avoid interpretation errors, calculation of sound paths of all potential indications is done as a part of the job preparation. Because line scans are used (all individual probes are moved along the weld at defined distances, optimized on a welded reference block, similar to pipeline AUT), only signals from potential defects will be recorded. This reduces errors (and thus missed flaws and false calls) to a high degree. Fig 12 shows a sample record. This makes the conventional TRL concept to be a reliable detection and sizing tool, without the need to evaluate flaws with additional techniques (the primary scan supplies all data necessary to assess indications in the sense of the code's acceptance criteria).

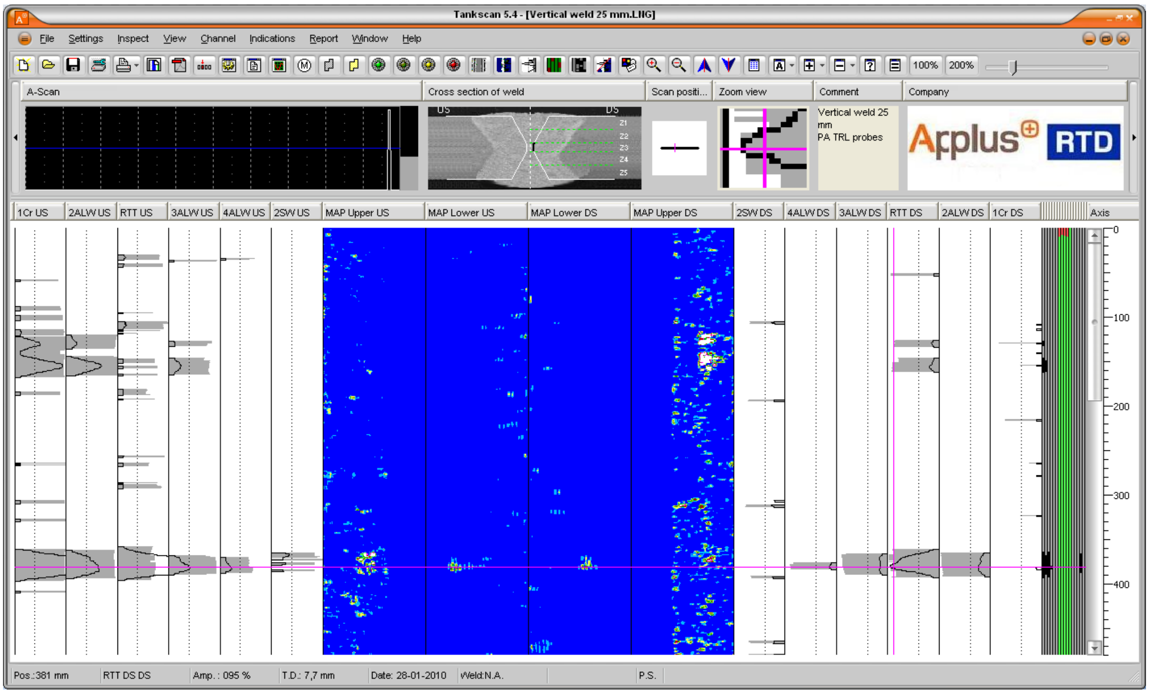

Fig. 12: Sample record of a line scan (similar to pipeline AUT)

NOVEL PHASED ARRAY DESIGN DEVELOPED BY APPLUS RTD

The advantages of the TRL technique were the reason to initiate the development of a phased array approach with properties similar to that of a multiple TRL probe arrangement. The following basic design criteria were used:

- The array concept must be able to simulate a multiple TRL probe arrangement, and must consist of one dual wedge with two arrays at either side of the weld
- The length of the array must be sufficient to cover a wall thickness range between 10 and 35 mm, facilitating all beam indices required to perform all techniques present in the conventional TRL arrangement (pulse-echo, RTT, creeping waves)
- The array lay-out (1D arrays) and wedge design should be in such a way that no lateral steering of the beam is required for individual zones
- For each zone, the area of the transmitting and receiving virtual crystal (azimuthal and lateral aperture) must be similar to that of conventional, optimized TRL probes, i.e. to accomplish a beam spread similar to that of conventional TRL probes

These basic design criteria led to a design as shown in figs. 13 and 14. The arrays are mounted on the dual wedge in such a way that the beam intersection area is always at the correct location, regardless of zone. No lateral beam steering is required. The arrays have the shape of a trapezoid, enabling the virtual crystal width in lateral direction smallest for short distances (upper zones), and larger for the larger distances. The element pitch varies along the array length according to a linear function (rear elements have larger pitch).

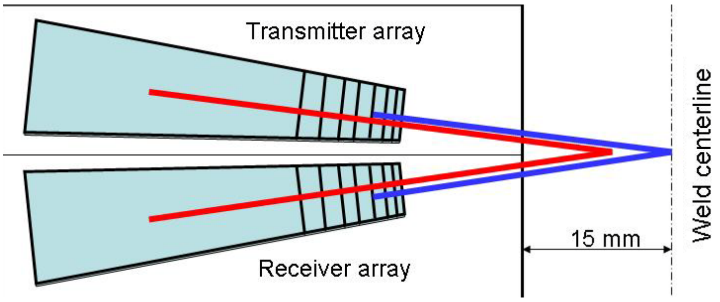

Fig. 13: New dual phased array probe design for austenitic weld inspection

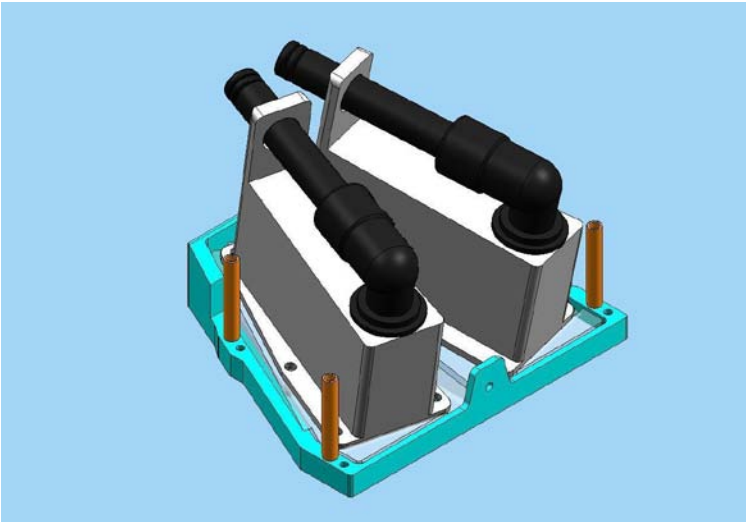

Fig. 14: New dual phased array probe for austenitic weld inspection

Apart from the properties mentioned above, the wedges are made out of the same material as that of other Applus RTD probes for AUT, which is stable against temperature changes. In this way, environment and material surface temperatures up to 100°C can be handled without noticeable changes in attenuation and probe angle (NDT directly after welding, high temperatures in tropical climates).

Fig. 15 shows the complete inspection system (scanner, power supply, laptop computer). The phased array electronics are mounted on the scanner frame.

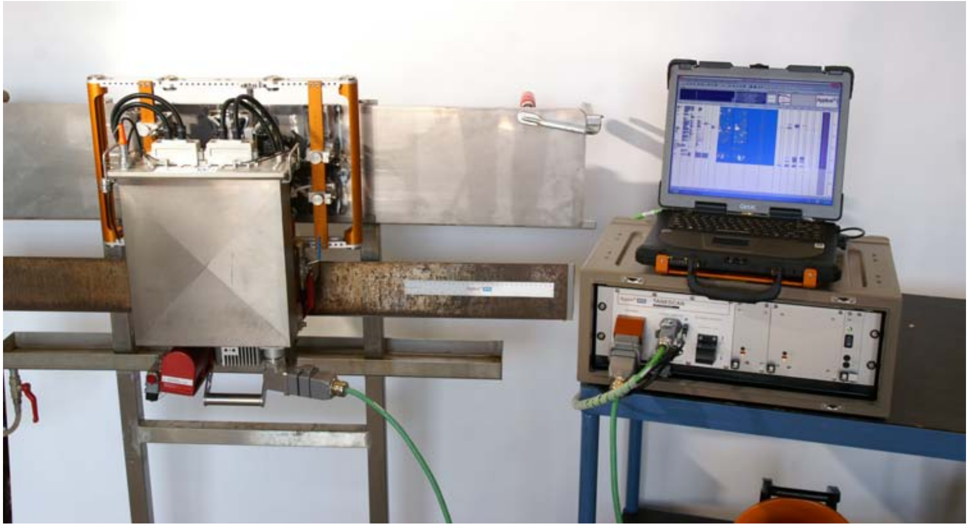

Fig. 15: Complete inspection system

Unlike many other phased array applications, visualization of ultrasonic results is not done in the form of sectorial images, but in a lay-out similar to that of pipeline AUT (strip chart lay-out). The lay-out is identical to the one used in combination with conventional TRL probes. This enables straightforward signal interpretation, because only relevant signals are plotted.

The result of this approach is a simple probe design requiring a limited number of phased array elements. Potential defects can be hit perpendicularly, enabling defect height sizing based on amplitude. This offers compliance to the code (API 620) without the need of additional (manual) sizing once an indication has been detected.

CURRENT STATUS

At the moment this manuscript is written, the new array design has been fully implemented. The redesign has been taken advantage of by implementing a new, compact electronics design, whereby the control electronics consist of a power supply and a laptop computer. Phased array electronics are located on the scanner frame.

Some validation exercises have been successfully completed, together with a major customer. It became evident that the system can comply with table U2 of API 620. Present work is directed to further optimization of phased array parameters and improving defect height sizing capabilities to meet table U1 of API 620.

CONCLUSIONS

A novel phased array approach for automated ultrasonic NDT of welds in LNG storage tanks has been presented. Unlike single-index sectorial scans, probe systems such as those using multiple TRL probes offer the possibility to detect and size defects in one go, thus complying with a major Code such as API 620, without the need for an additional sizing exercise once indications have been found. The novel phased array approach is designed to mimic multiple TRL probes, thus combining optimum detection and sizing, minimum false calls and straightforward interpretation.

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