Automated ultrasonic testing of seamless steel pipes with matrix arrays

Abstract

Seamless pipes are demanding and high-technology products. Especially in the oil and gas industry, but also in power plants, they are subject to the most stringent quality requirements. Ultrasonic NDT benches are ideal to detect potential inhomogeneities at industrial speed in rough environments. Using Phased-Array technology with additional Paint-Brush technique gives the opportunity of gapless detection up to ± 45° relative to the axial orientation at full production speed [1]. The use of 2D-Phased-Array Transducers has the potential to overcome this limitation, since they naturally allow to detect defects under any orientations. Within this paper, we present a fully parallelized, automated pipe testing machine which has significantly improved the possibilities of comprehensively testing seamless steel pipes at full production speed. It is based on a 2D-Array with more than 700 channels, capable to detect inhomogeneities oriented on the full circle in a gapless way, embedded into a 2-carriage gantry solution operating in an industrial environment at a Vallourec mill located in Düsseldorf-Rath (Germany).

Due to the high elongation involved in the production process, most of the surface imperfections on hot-rolled seamless pipes are positioned in a predominantly longitudinal direction. However, it may happen, that other inhomogeneities orientations can occur, which raises the interest, to test the steel pipes for larger angle ranges, ideally for all potential oblique orientations. Using standard methods, a series of transducers is needed, to close the full circle (360°) of potential defect orientations. A series of transducers, each for a specific angle, is impractical for cost, speed and maintenance reasons

1. Introduction

Basically, imperfections can be characterized by their length and their orientation. The orientation of the imperfection is described by an angle, which is defined by the rotation angle ($\boldsymbol{\varphi}$) of the imperfection axis ($\boldsymbol{x'}$) with respect to the longitudinal pipe axis ($\boldsymbol{x}$) (see Figure 1, left). According to current standards, artificial defects like reference notches shall be detected from two sides corresponding to the opposing sound direction I and II, respectively. Based on this, a typical nomenclature for these reference notches combines the orientation and the sound beam direction. Taking into account all possible orientations for detection it is handier to introduce the polar projection angle ($\boldsymbol{\phi_x}$) for clear assignment. An illustration of both nomenclatures is given in Figure 1 on the right.

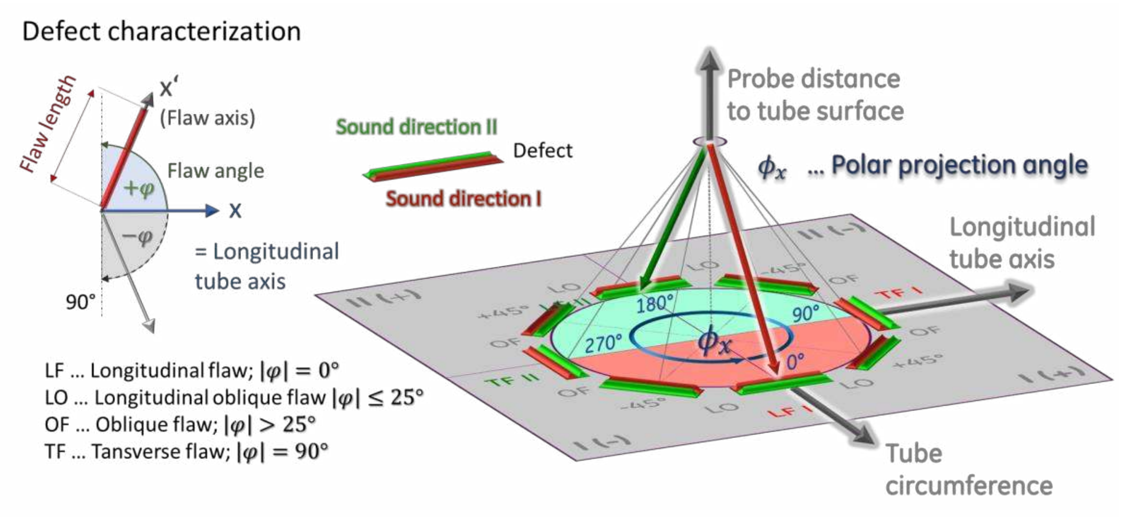

Figure 1. Defect characterization including the definition of the defect orientation

2. Holographic sound fields with ShapeUT™

An acoustic hologram must be produced to detect the full circle (360°) of potential defect orientations with just one array probe. By combining sophisticated phased array technology with the implementation of pulse shape laws, ShapeUT™ provides industry's first gapless 360° oblique inspection method for seamless pipes and pipes. The implemented pulse shape laws represent an extension from existing techniques based on delay laws for the pulse emission of single elements to a calculation of the complete excitation function for the single elements. Applying appropriate pulse shape laws to a 2D matrix array it is thus possible to create ultrasonic holograms and to produce sound fields with superior properties with additional Paint-Brush technique filling the gap in oblique flaw detection of current state-of-the art machines (see Figure 2). ShapeUT™ uses the USIP|xx electronics platform [2].

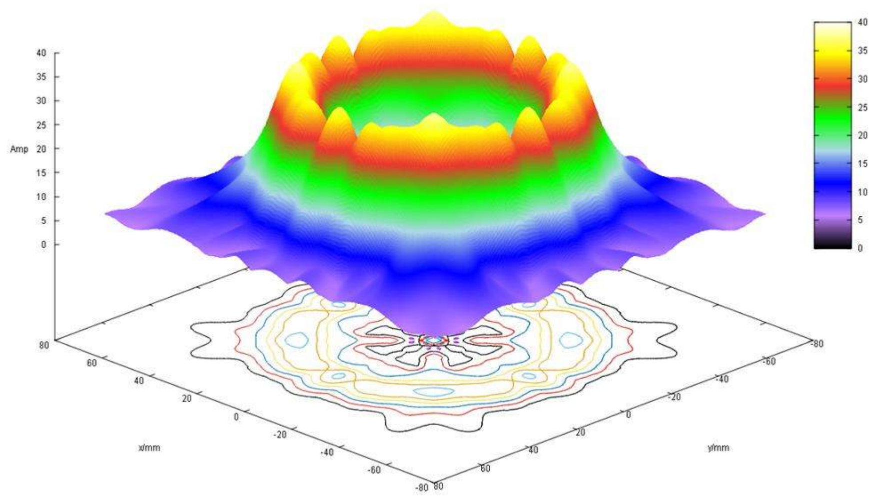

Figure 2. A representative sound field generated by the ShapeUT™ function in 360 degrees

3. UT machine

3.1 Setup of the UT machine

A 2D matrix probe in combination with ShapeUT™ was successfully embedded into a 2-carriage gantry solution for industrial application at Vallourec. The fully parallelized, automated ultrasonic testing (UT) machine is capable to detect imperfection oriented on the full circle in a gapless way. Moreover, a high precision wall-thickness measurement and lamination detection can be performed to fulfil requirements of valid standards. An illustration of the mechanical setup of the carriage is shown in Figure 3.

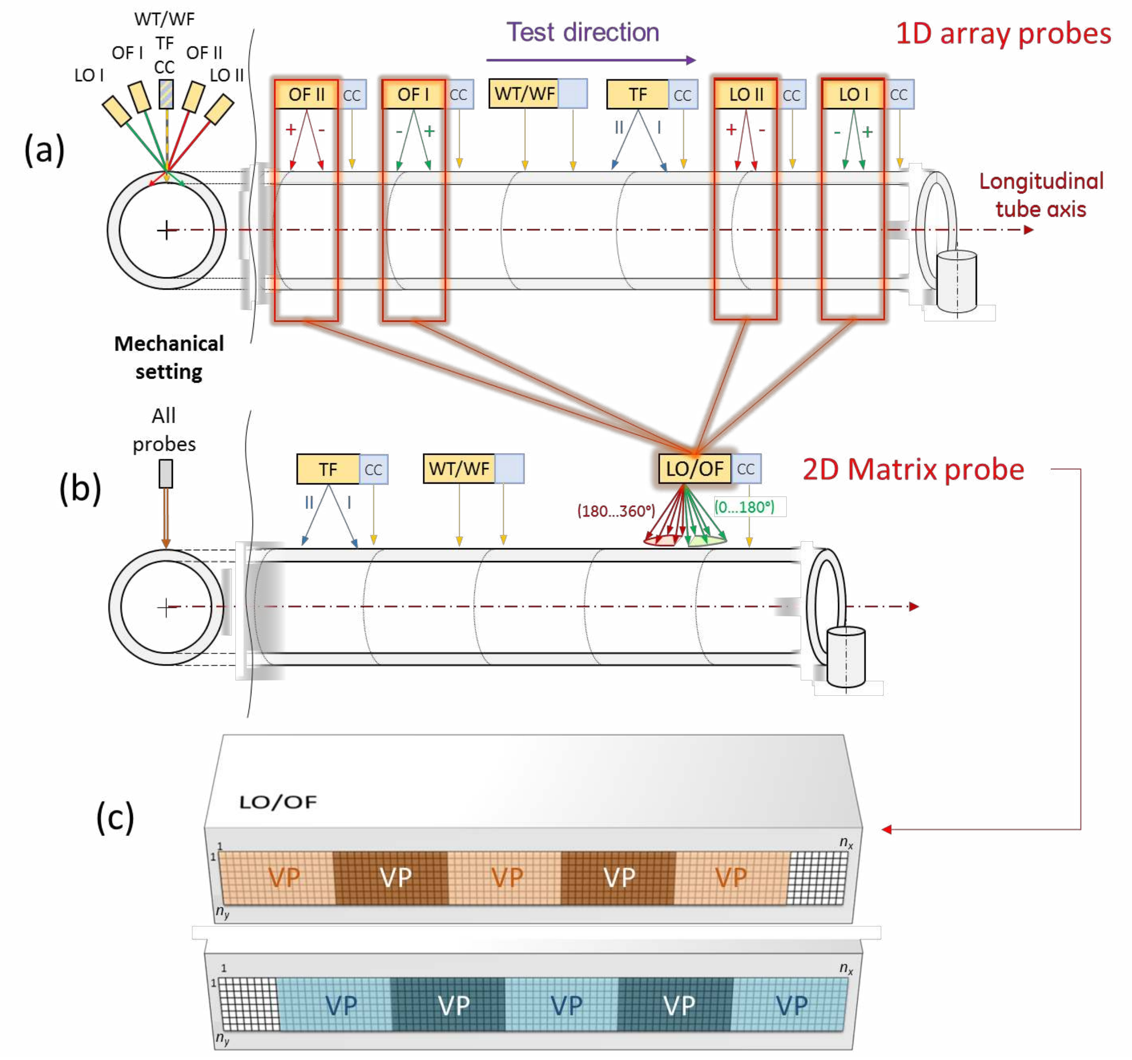

Figure 3. State-of-the-art UT system equipped with 1D array probes (a) in comparison to the new system including a 2D matrix probe (b). Schematic sketch of a possible configuration of virtual probes (VP) is shown below (c).

To cope with the large number of channels for the flaw detection, the USIP|xx electronic platform [2] provides high parallelisation and fast post-processing of measured data in subsequent steps (Paint-Brush) without any new acquisition. This specific Paint-Brush technology is based on a Vallourec patent and was developed for industrial usage with an exclusively license by GE. In this way it is possible to ensure the operation at full production speed. Typical inspection cycle times for the installed machine are in the order of one minute, but they can vary depending on pipe diameter and pipe length. With the current configuration of the system an overlap of the virtual probes of 50% is achieved.

3.2 Layout of the UT machine surrounding

Figure 4. The installed 2D-matrix UT-machine at the Vallourec mill in the Düsseldorf-Rath, Germany.

The UT bench, which was installed at the Vallourec mill located in Düsseldorf-Rath is a portal system with two carriages, two separate operating roller conveyors and operator stations (see Figure 4). All UT testing results are transferred into the operator cabinet, so that everything can be monitored from there along with the control of the pipe transport. The portal is built in a way that each carriage can move over the two separate turning conveyors independently, so that the two carriages can operate individually on the different turning conveyors on different pipes. For big orders it is also possible to operate both together on one pipe. Due to the high flexible installation it is possible to reach good productivity even with smaller lots, because during UT testing with one carriage of an order it is possible to calibrate the other carriage for the next order.

Table 1. Equipment of the installed UT machine

Item	Probe	Type	Test function
1	LO / OF	2D matrix	360° Longitudinal and oblique flaw detection
2	WT / WF	1D Array	Wall thickness measurement and lamination detection
3	TF	1D Array	Transverse flaw detection
4	CC	Single transducer	Coupling control 2D LS/SF
5	CT	Single transducer	UT-transducer for additional purpose
6	CC	Single transducer	Coupling control TF

To ensure industrial testing speed and to include other test functions, additional probes have been installed on each carriage beside the 2D matrix probe. The complete list of used UT probes, types and corresponding test function of one carriage are given in

Table 1. The added probes are used for the high-resolution wall thickness measurement and testing for laminations as well as for defects with a transverse orientation.

4. Measurement results

The 360° detection was validated with various reference pipes all over the specified dimensional range of the UT machine. Results shown here are from one reference pipe with a nominal outside diameter (Ø) of 244 mm and a nominal wall thickness of 12 mm (Ø 244 mm × 12 mm). One C-Scan of this reference pipe is illustrated in the middle of Figure . The reference notches have a nominal depth of 5% of the wall thickness and a length of 25 mm (1 inch) covering the full circle in steps of 5°.

4.1 Changeover and calibration principle

To calibrate a Phased Array UT bench usually a high-resolution scan around the specified reference notch is performed to ensure a proper setting of all virtual probes. Because the production of a calibration pipe with many flaw direction angles covering 360 degrees in small steps is costly, a compromise has to be realized for industrial use. Therefore, the adjustment of the UT machine is done on pre-defined master channels with a corresponding reference notch on the reference pipe. Typically, these are the main flaw directions known from standards. Gain values for intermediate channels (slave channels) are automatically interpolated. Besides this approach, the VRCF has developed an alternative calibration method, which will be compared to the described one in the near future.

For the 2D probe, ShapeUT™ provides a full electronic setting of the incident beam angles. Mechanical work on the UT machine to optimize the incident angles for different pipe dimensions is no longer necessary. Taking also into account that the 2D probe substitutes four 1D array probes for the oblique flaw detection, the mechanical changeover time (dimension change) is significantly reduced compared to state of the art machines. All electronic settings are pre-stored and can be loaded in the UT software. Software wizards were developed for the calculation of pulse shape and delay laws. All this leads to a simplified handling of the UT machine so that fast overall changeover times can be achieved.

4.2 UT inspection runs

The presented UT results were all taken from inspection runs which were performed under full production condition based on a calibration according the above described method. For the master channels notches with an orientation of 0°, ± 20°, ± 45°, ± 65° and 90° were selected. For each inspection run C-Scans were recorded and afterwards analysed. In the upper and lower part of Figure 5 the UT results for the master channels of the corresponding C-Scan part (middle) are shown in the polar projection visualization.

The colour-coded representation of the C-Scans reflects the deviation of the measured amplitude of the UT response to a given reference level. It is one of the new visualization features, which makes this UT machine operational. A positive value is shown with a scale from light to dark red and means that the measured amplitude is higher than the set reference level. Negative values (dark green to light green) imply that the UT response is lower than the set reference level. For reasonable data reduction, a minimum value can be set to cut the noise (low UT amplitudes).

Typically, the reference level corresponds to the threshold height for the event triggering. Looking to each master channel it is obvious that all corresponding reference notches were clearly detected. For example, in the ± 65° master channels (left bottom) the reference notches with a flaw angle of + 67° and - 67° are clearly detected (red) in the respective opposing directions [65°; 245°] and [295°; 115°]. In the given example there are some indications with green colours, which refer to slave notches. For these, the event threshold was not adjusted but taken from the master channels. The adjustment of the reference level for slave channels (level correction) is underway.

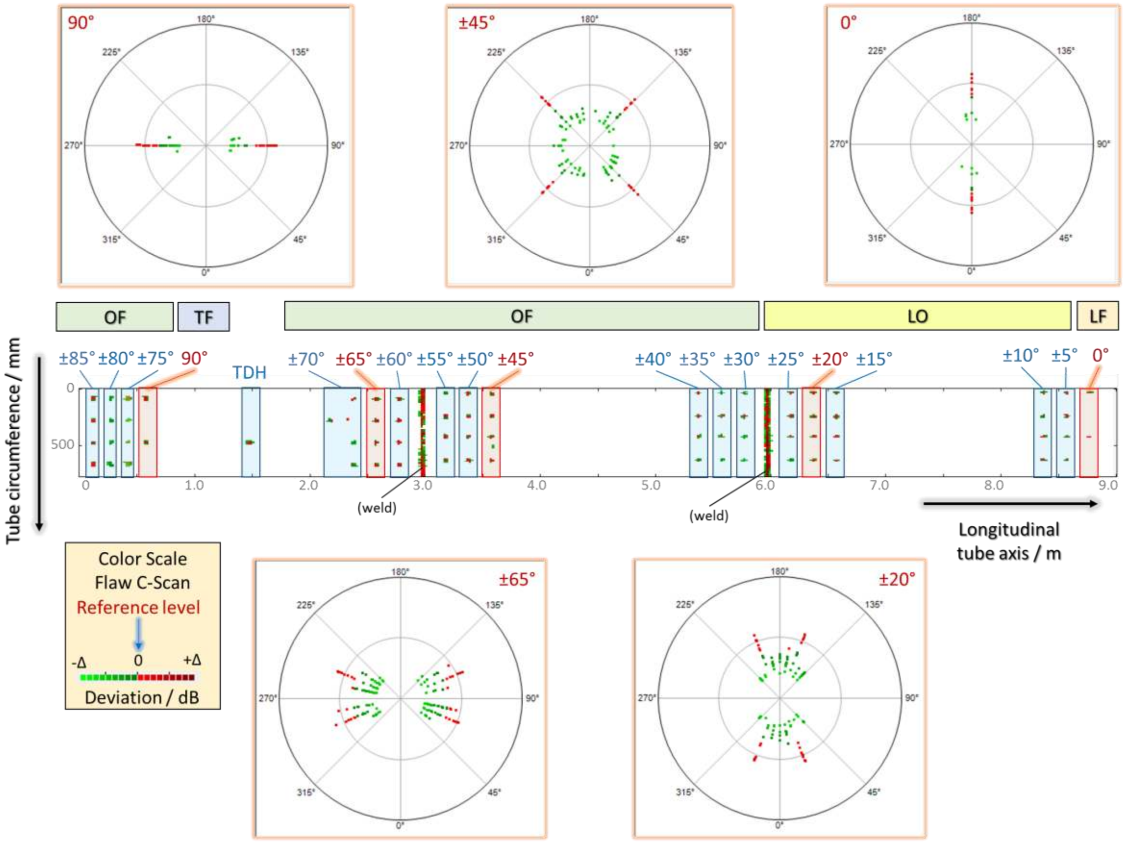

Figure 5. C-Scan for flaw amplitudes obtained for one inspection run with the reference pipe (middle). Reference notches are manufactured at inner and outer pipe surfaces resulting in a total of 142 notches. There are 4 notches per section for oblique direction (LO, OF) and 2 notches for the longitudinal (LF) and transverse (TF) direction. Areas with master and slave notches are highlighted in red and light blue, respectively. The colour scale for the UT amplitude corresponds to a deviation in dB with respect to a reference threshold. The corresponding polar representation of the UT amplitudes for the adjusted master notches are shown at top and bottom.

4.3 UT inspection results

To demonstrate the reproducibility of all oblique orientations ten subsequent inspection runs with the reference pipe were performed. Afterwards the UT response for each notch was checked and additionally compared to the UT response of this notch in the other inspection runs. All reference notches were detected for each inspection run thus allowing a complete analysis of the measured data.

In Figure 6 the summarized result for all reference notches in dependence to the polar orientation is shown separated for internal (left) and external (right) reference notches. In the upper part the average UT response of the reference notch in relation to the targeted value for the adjusted master notches is shown (dot) along with the deviation (thin line). Due to the calibration method the master reference notches level around 0 dB. In addition to the measured flaw amplitudes, the noise is plotted in the same diagram. As the noise level varies over the considered angle the average noise level is illustrated as orange line together with a tolerance band, which shows the standard deviation of all angles.

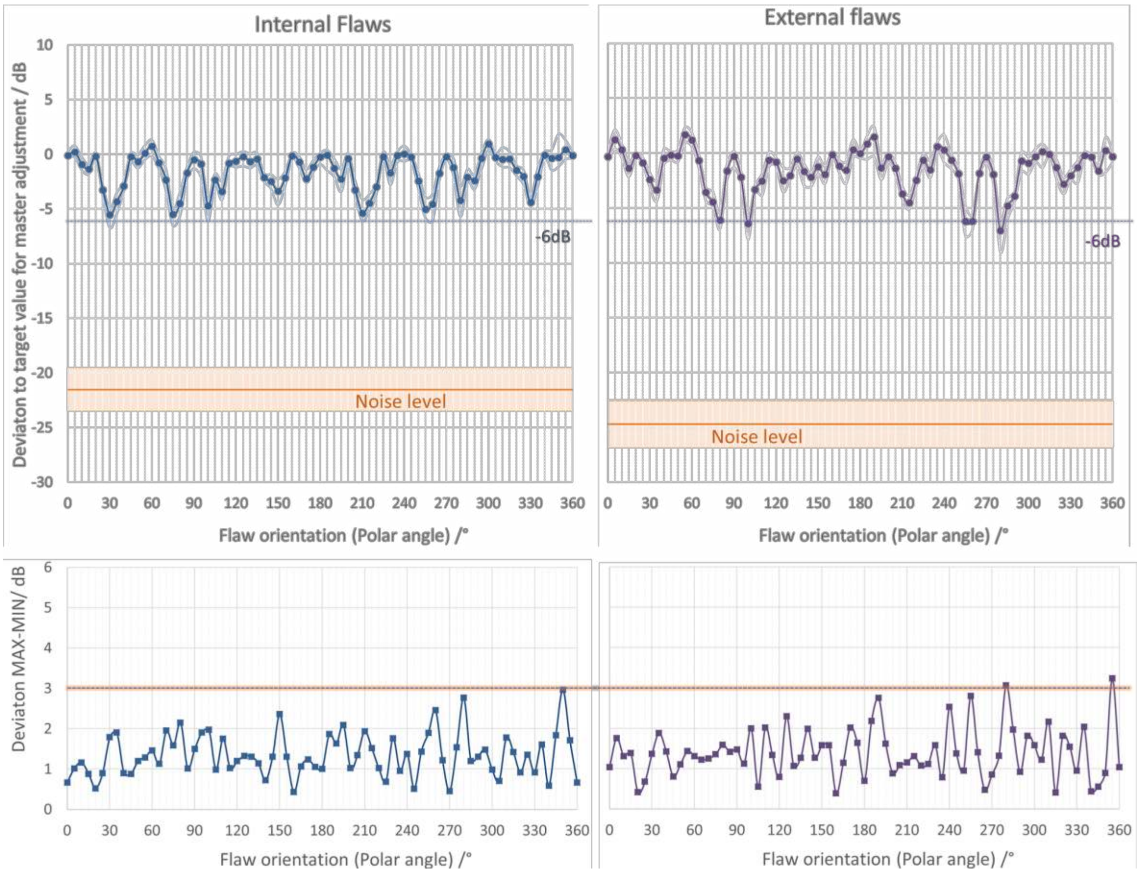

Figure 6. Results of ten subsequent inspection runs performed with the reference pipe. Top: Sensitivity of flaw detection plotting the deviation of the measured flaw amplitude to the target value of the adjustment of the master notches as a function of the polar projection angle. In addition, the noise level is shown indicating that for the entire circle of 360° the signal-to-noise ratio (SNR) is well above 12 dB. Bottom: Ratio of maximum to minimum measured amplitude in the 10 runs as a function of the polar projection angle

A comparison of the noise level with the distributions for the measured amplitudes shows that the signal-to-noise ratio (SNR) for all reference notches is safely above 12 dB, out of that an industrial testing to all oblique orientations can be performed for internal and external defects. The deviations of the interpolated notches compared to the target level of the adjusted master channels are in average (-3) dB and stay within (-6) dB except of the polar angle of 280° (external flaws) with a maximum deviation of (-7) dB. This means that the threshold can be set for all channel still with sufficient distance to the noise level.

At the bottom of Figure 6 the absolute deviation of the UT responses of all runs in dependence to the polar angle is shown. This absolute deviation over all inspection runs is in average below 2.0 dB and at maximum below 3.2 dB. Taken into account that not all 142 reference notches can be manufactured with the same UT response homogeneity, the single events with higher variations are outlier values.

5. Conclusions

With the set-up of the latest UT machine, installed at the Vallourec Düsseldorf-Rath location, an oblique UT inspection in directions over the full circle (360°) could be achieved. This was reached by replacing several 1D-array probes needed for the oblique flaw detection before with a 2D-matrix probe in combination with ShapeUT™, which uses the USIP|xx high-end ultrasonic testing electronics platform. As for this UT machine most of the set-up is electronic work, fast changeover times can be achieved as known parameter sets can be reloaded.

Despite the large number of channels, inspection can be performed at typical production speed due to high-performance electronic platform featuring high degree of parallelisation as well as post-processing of the acquired data. The repeatability analysis shows a high accuracy of the measurement with an SNR > 12 dB and a reproducibility of the UT signal response of typically below 2 dB. It was demonstrated that the new UT machine has an outstanding detection capability which can be taken as a criterion for the quality of the UT inspection.

Additional to the described application the usage of the 2D matrix does not only allow single flaw detection over the full circle range but also the detection of a more complex pattern.

References:

1. Breidenbach et. al., “New Phased-Array Ultrasonic Testing Gantry with Extended Testing Functions for Testing of Hot Rolled Seamless Steel Tubes and Pipes”, ECNDT 2014, Prague, Czech Republic