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Automatic Systems for Ultrasonic Inspection of Pipelines (survey)

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Abstract
Pipelines are responsible industrial facilities used to transport oil products. They consist of tubular modules joined to each other by welding. The main deviations from the integrity inspected by non-destructive testing methods are the thinning of the parent metal and discontinuities in the welded joints. This is the radiographic method that has traditionally been used long years to inspect the welded joints. In recent years, with the development of mechatronic systems, the application of semi-automatic and automatic pipeline ultrasonic inspection systems has been increased over the use of radiography. The implementation of computer control, through algorithms for processing the collected information signals, provided the possibility of displaying the inspection information in two-dimensional images. In this paper, an overview is made of the commercial pipeline ultrasonic inspection systems, their capabilities and limitations, as well as specifications and techniques for their application.

Keywords: automatic ultrasonic inspection, two dimensional images, engineering critical assessment (ECA), electronically scanning systems, mechanized scanning systems.

1. Introduction

Over the past years automated ultrasound systems have been used to inspect pipelines providing high-speed testing and precision of results. Depending on which side of the pipe wall the automated ultrasonic systems are coupled, they are divided into scanning pipe from OD surface and scanning pipe from ID surface. The former are mainly used in production to inspect welded joints and base material. The latter are used in service to inspect the base material for damages caused by corrosion and erosion.
The implementation of mechanized system for pipe external inspection of welds began in 1959 with development of the first mechanized ultrasonic system "Rotascan" for inspection of girth welds patented by the Netherland Company RTD [1]. It consisted of three flaw detectors with three single-element probes, two angle on each side of the welded joint and one normal. For the first time, a multi-channel automated inspection system using encoder was developed in 1972. It consisted of a four-channel instrument with four probes. Later, single-element probes were replaced by multiple element phased array probes.
The mechanisation used for pipe internal inspection automated systems started its development many years ago being developed to clean pipes from dirt, corrosion and deposits. Subsequently, automated systems, called intelligent pipe internal inspection systems, are developed. The earliest system, developed by Shell Development in 1961, applied electro-magnetic methods to collect information. For the first time an ultrasonic pipe internal automated system for corrosion inspection was developed in 1986. In 1997, it was introduced into an automated system and angle probes to detect crack type discontinuities.
Modern automated ultrasonic inspection systems apply the basic principles of ultrasonic inspection using phased array and time-of-flight diffraction techniques. Algorithms were

developed to manage the transmission and receipt of several probes or probe elements at the same time, and to further process the scanning signal records displaying the information in the form of two-dimensional images [2, 3]. The capability of the phased array probe to focus the ultrasonic beam in the inspection area and the small focal spot size of 2 mm allowed the welded joints to be inspected in separate zones. A new type of Criteria for Assessment – Engineering critical assessing (ECA) was developed, subject to the principles of fracture mechanics and assessing discontinuities by their indication height.
This improved the probability of detection and sizing transverse discontinuities in welded joints oriented along the pipe radius. The use of focussed probes and zonal discrimination method for the welded joint defines the advantages of this method over the radiographic methods of weld inspection. The introduction of computerized control to collect information with several ultrasonic probes led to a reduction of inspection time and increased volume of inspected area in automated pipe internal inspection of the main material of in-service pipes. Methods of weld inspection using ionizing radiation sources and X-rays were replaced by a pipe external mechanized ultrasonic inspection of welds.
The purpose of this paper is to determine the types of ultrasonic scanning systems available on the market and their images, and both capabilities and limitation of pipeline inspection techniques.

2. Ultrasonic inspection of pipelines for discontinuities

Pipelines are produced from seamless pipes or rolled sheets welded by longitudinal or spiral weld seam. Depending on the pipeline service conditions under specific safety class, the grade and dimensions of pipes are defined by normative documents. Approved steel grades and ranges for production of pipelines are given in API 5L, ISO 3183 EN, 10208-2 and ASME / ANSI B 36.10M. The most commonly used steel grades are X70 (around 63%) and X65 (about 12%) according to sales data from ArcelorMittal. The length of pipes produced for pipelines starts at 3m and can reach up to 15m. The outside pipe diameter starts at 20mm and reaches up to 1400mm. Seamless pipes are produced of an external diameter up to 400mm. Pipes of welded rolled sheets with spiral or longitudinal weld are produced to an outside diameter of 1000mm and with a longitudinal seam only of up to 1400mm outside diameter.
In the gas pipelines material, there is a significant quantity of defects that have arisen in the production process of pipes and welds as well as during their installation and operation. Defects occurred in the pipelines production process are: integrity damages of the basic material and in the welding joints, deviation in the physical-mechanical properties. The defects in the installation and construction of gas pipelines are related to pipe laying problems, disruption of the insulation coating, mechanical wear, and introduction of increased mechanical stress into material. In operation, defects are related above all to corrosion and erosion damages, changes in the mechanical stress condition, due to nature impacts, fatigue cracks, changes in the material structure at loads higher than the operational, etc. Data presented in [4] show that the percentages of external corrosion defects in service are 29%, of internal corrosion – 2.5%, due to installation mistakes – 23%, due to operation mistakes – 16% and due to pipe production in factories – 14%. In the event of defects that break the integrity of the gas pipeline, gas leakage occurs, often resulting in significant material losses (gas loss, fires, and atmospheric pollution) and, in some cases, death of people.
In recent years, the ultrasonic method with its various mechanised applications for pipe internal and pipe external inspection has proved itself as the most promising method of non-destructive inspection and diagnostics of discontinuities, mechanical condition and physical-mechanical properties.

In manufacture and installation of pipes, basic material and welded joints are inspected by the conventional ultrasonic techniques for manual inspection as set out respectively in the standards EN 10160 and EN 17640. The inspection is carried out in contact by single element normal and angle probes. During operation, the welded joints are re-examined according to the requirements of EN 17640 and the basic material is examined for corrosion and erosion defects according to the requirements of EN 14127.

3. Types of scanning systems and images

The basic elements that make up an automated scanning system are: scanner head, battery, data collection devices, visualization, records, and contact medium supply. The scanner head includes a drive motor (system mechanisation), position encoders, contact medium distribution system, piezo-composite and / or ToFD probes and wedges (Photo 1) [1, 5]. The data acquisition device includes an ultrasonic multiplexing system and a digital signal processing system. Through the multiplexing system each channel can be monitored as a separate instrument with a separate A-image, the operator can configure each ultrasound beam individually. By means of a microprocessor controlled by the control center various data can be collected and processed such as motor speed and direction of motion, temperature, monitored screen data, sampling interval, encoder calibration, etc. [6, 7].
The major manufacturers of automated ultrasonic inspection systems for pipelines are: Olympus Corporation – Canada, JIREH Industries – Canada, IMG Ultrasuoni – Italy, Phoenix Inspection Systems Ltd – England, APPLUS+RTD – Netherlands, DACON inspection services – Norway, ECHO+ – Russia Rosen and LinScan.

(a) (b) (c)

Photo 1. Head of pipe internal (a) and pipe external (b) scanner and wedge (c).

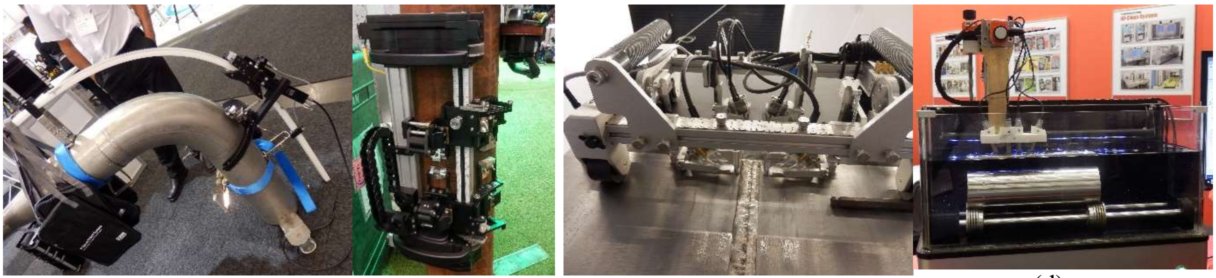
The level of automation of the ultrasonic system is defined by the availability of the above-mentioned basic elements. If all elements are included in the ultrasonic system, it reaches complete automation and is called an automated ultrasonic system. In the absence of one of the basic elements in the ultrasonic system, it is partially automated and is referred to as semi-automated. From the point of view of mechanization of the ultrasonic system, it is divided into manual and mechanized. Globally recognized scanning systems are three main groups:
- manual / time-based, free moving/,
- semi-automated /with encoder, no motor/,
- automated /with encoder and motor/.

3.1. Automated scanning system

The automated scanning system serves to move the probes on inspected surface, in most cases an encoder is added to record the probe movement. To encompass a larger test volume more than one probe or multiple elements phased array probes are used controlled by an electronic scanning system. It is used to guide the beam, acquire information and visualize it in two-dimensional images.

3.1.1. Pipe external inspection

At present, three main types of drive mechanisms are produced: with chain and without magnetic wheels; only with magnetic wheels and a combination of both (photo 2 taken at the ECNDT 2018 conference in Gothenburg, Sweden). A major drawback of chain drive mechanisms and wheel drive mechanisms is that moving the probes on the inspected surface gradually alters the position of the scanning head relative to the test object. The operator has to guide them so they do not deviate from the specified scanning path. Deviation from the scan path affects the location and dimensions of the indications of discontinuities on the images, offsetting them from their actual positions and dimensions. Another drawback of magnetic wheel scanners is their inability to be used on non-ferromagnetic materials. When inspecting tubes with small diameters, it is possible to use an immersion bath mechanized system moving probes of two axes and / or moving the tube along the generant and / or circumference (photo 2c).



(a) (b) (c) (d)

Photo 2. Mechanised systems: with chain, no magnetic wheels (a), combined with chain and magnetic wheels (b), with magnetic wheels only (c) and immersion bath with mechanised system (d).

3.1.1. Pipe internal inspection

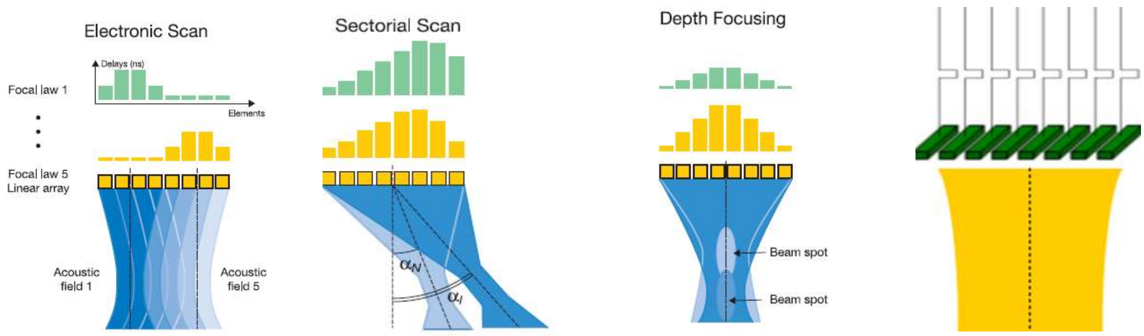
The automated system motion along the pipe axis is carried out in two ways, by actuation through the fluid supply pressure inside the pipe or on wheels driven by a standalone motor powered by battery. A schematic diagram of an automated ultrasonic system is given on photo 3a. When electronic scanning is not applied, additional motion of the head with probes is performed in order to cover a larger test volume. In most cases, before the scanning head there is another one to clean the surface of the pipe from dirt, or the scanning head has cleaning parts. To control the speed of motion of the automated system there is a bypass valve to pass a portion of the pressurized fluid in order to reduce the scanning speed. The automated system position is monitored by an encoder and a GPS device.

(a) (b) (c)

Photo 3. Schematic diagram of pipe internal automated system (a), scanner head (b) and automated system in a pipe (c).

3.2. Electronic scanning system

Electronic scanning systems control the multiple element probe pulsing/reception by a multi-channel computer system with a multiplexer. The number of probes or elements operating simultaneously in a given scheme (tandem, different pulsing angles, beam focusing, etc.) is determined by the number of channels of the multiplexing digital device. In addition to individual probes / elements operating in a specified pulsing/reception scheme, electronic scanning allows to create ultrasonic field directed in a desired test area by complex pulsing of several probes / elements. The shape of the field and its spatial orientation is defined by the delay set of pulsing/reception of the individual probes / elements. The ultrasonic flaw detectors available on the market operate phased array probes of 8 to 256 elements and are controlled by a 16 to 64 channel multiplexing digital device. The most commonly used pulsing / reception technique for electronic scanning systems is artificial aperture pulsing. In this case, each element of the active group emits and receives simultaneously, being controlled by a separate multiplexer channel. It is the most commonly used technique, because for a short period of time the received signals build an image with a good resolution for the practice.



a) linear scan b) sectorial scan c) dynamic depth focusing d) unfocused PA probe

Figure 1. Types of electronic scanning: linear (a), sectorial (b), dynamic depth focusing (c) and no elements delay set (d) [8].

The following 4 basic techniques of electronic scanning [8] are used in commercial phased array probe instruments:

- linear scanning (E-scan) – scanning takes place at a fixed angle on the active axis of a probe from several active groups, the electronic scanning step is usually every following element, but can also be set over a larger number of elements (see Figure 1a).
- sectorial scanning (angle, S-scan) – ultrasonic beam has a specific sweep range using the same active group of elements (see Figure1b).
- dynamic depth focusing (DDF) – The active group uses different focal laws with different focal lengths to distribute ultrasonic waves in the object (see Figure 1c).

- no elements delay set –The active group operates with a delay law set, which sets the delays of the emitted waves tending to zero, the phased array probe is unfocused and acts as a mosaic multi-element probe (see Figure 1d)

3.3. Images

The automated ultrasonic inspection systems for pipelines offer several basic types of display:
- bar chart with amplitude and time information for each scan step,
- identification of zones and position relative to the centre line – position of indication along the scanning axis and in depth,
- axial position from the scanning start point position,

A combination of mechanical and electronic scanning allows inspection data to be presented in various types of images shown in Figure 2 [8]:
- A scan – each active group gives an A-scan, that is sum of the A-scans of each separate element in the group controlled by a channel. Number of A-scans depends on the number of active groups used in the phased array probe;
- B scan – side view of the object (perpendicular to the axis of mechanical scanning);
- D (E or S) scan – end view of the object, in linear scanning (E-scan) or in sectorial scanning (S-scan). The image is perpendicular to the electronic scanning axis, shown in green in Figure 2;
- C scan – top view of the object.

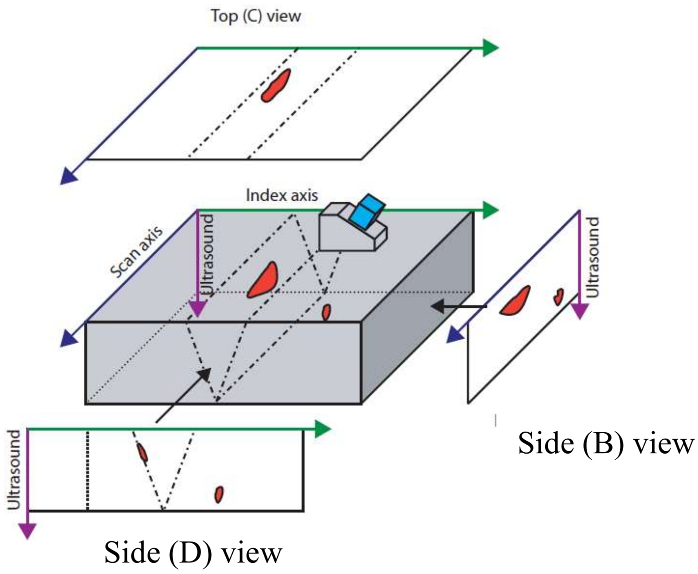


Figure 2. Views of two-dimensional images.

Inspection of welds with phased array probes allows for additional type of information display in the form of strip images (see Figure 3 inspection and zone-discriminated "strip" charts). The individual active groups of elements of the phased array probe are set to transmit and receive so that their beams intersect in the test area (see Figure 3 settings). The strip images are plotted with two axes, one giving the length of the welded joint in mm, and the other the echo signal amplitude, proportional to the reflective area. The length of the welded joint is recorded with a mechanical scanning encoder, giving the position of the probe through a predetermined displacement step. The amplitude is adjusted to a side drill hole. The colour code of the signal reflected in the inspection corresponds to the colour of the inspected section set to a specified level in percent of the screen. The method of indicating signals above a certain threshold is applied.

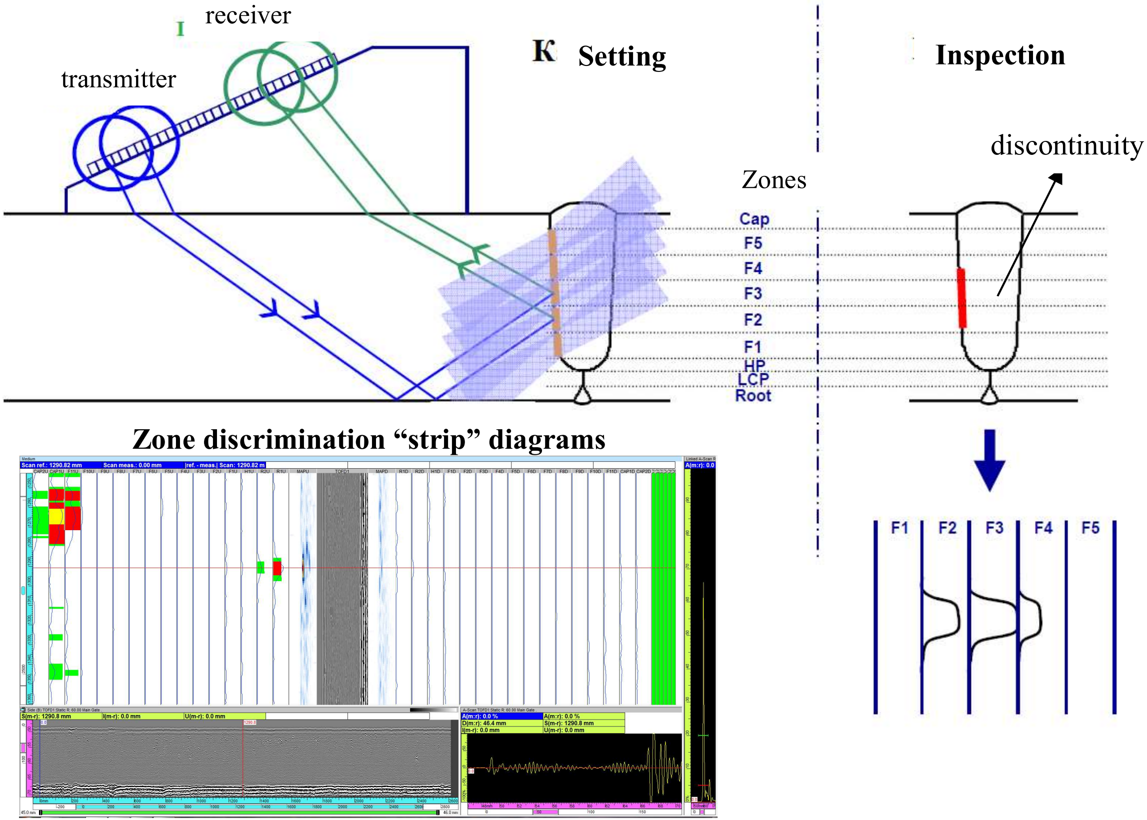


Figure 3. Scheme of inspection and „strip” charts of zone discrimination of weld.

With pipe-internal automated scanning systems the images are displayed along the pipe axis from the start of the scanning. The combination of electronic and mechanical scanning allows the inspection information to be displayed in the form of B and/or C-scans. The wall thickness information is given by WT (wall thickness) and SO (stand-off) C -scans in colour code corresponding to, respectively, the thinning of the wall from the outer and inner surface of the pipeline wall. Thinning is determined by the pulse-receiving time, by monitoring the echo signals from the inner and outer surfaces.

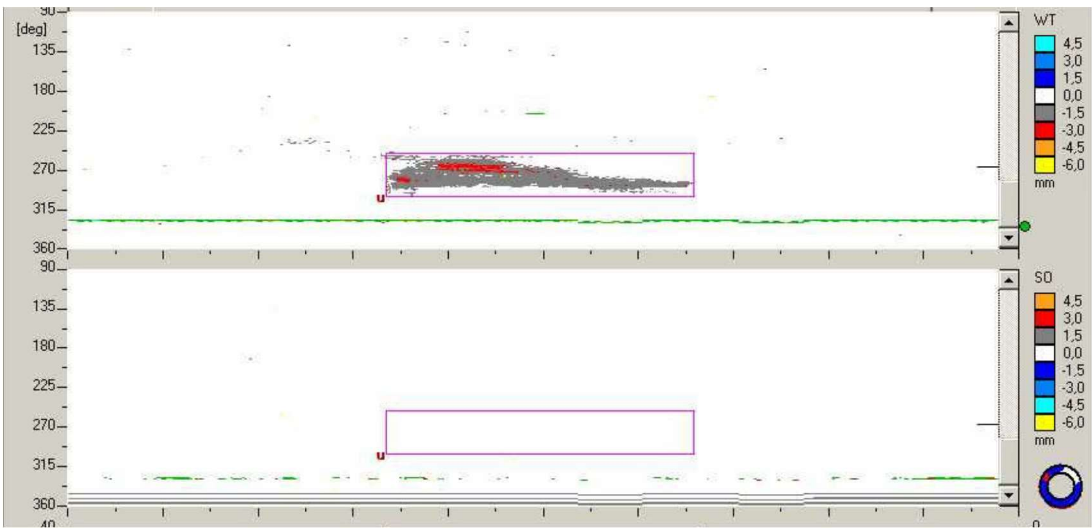


Figure 4. C–scan in pipe internal ultrasonic inspection.

Figure 4 shows two C-scans in sequence to determine the thinning of the outer and inner surfaces of the wall [9]. On the Y-axis the distance on the circumference is given in degrees from a given start point, and on the X-axis, the distance along the pipe axis from the start of the scan. Figure 5 shows a typical B-scan to find deviation from the wall thickness [10].

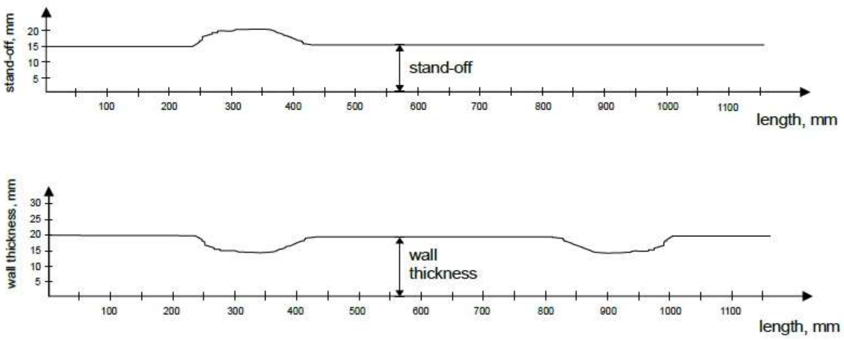


Figure 5. Principle of ultrasonic determination of wall thickness and B – scan in pipe internal ultrasonic inspection.

4. Specifications and techniques for automated ultrasonic inspection and assessment of pipelines

4.1. Pipe external inspection

Until 1998, inspection by mechanized ultrasonic systems of welds in pipelines was performed according to manufacturer's specifications. In 1998, ASTM E-1961 was published, where calibration and setting of the automated system for the relevant test zones of the welded joint were regulated. The evaluation of the indications registered is carried out on the basis of:
-Workmanship criteria,
-ECA criteria,
The application of phased array probes for automated inspection of welds is regulated in EN ISO 13588 and time-of-flight diffraction technique is regulated in EN ISO 10863. The evaluation of welded joints by the technique using phased array probes is carried out according to EN ISO 19285.
In the pipe external mechanized system, the probes are coupled to the surface of test object by a layer of water fed by a pump through the wedge holes. In order to achieve consistent contact, this layer should be less than half the length of the ultrasonic wave. In some cases, this is achieved by pins lifting the wedge above the contact surface at the desired height. Inspection schemes are specified in EN ISO 13588 according to test levels, two of them are shown in Figure 6. A combination of mechanized scanning with linear and sectoral electronic scanning is applied. In order to obtain a two-dimensional image in the data acquisition, a mechanism of moving the probe is used and encoders are used to obtain information about the probe moves on the test object.
After selecting a scanning (ringing) scheme, a sensitivity adjustment for each transmitted ultrasonic beam (beam angle, focus, etc.) shall be carried out with the phased array probe and wedge if used. Different focusing modes (static or dynamic focusing in depth) are applied, the sensitivity being adjusted for each focal distance. The use of Angle Corrected Gain (ACG) and Time Corrected Gain (TCG) allow the correction of signal amplitude for all beam angles and all distances to be set at one evaluation level. The amplitude correction is performed by a side drill hole type of reflector located at a different distance from the probe.

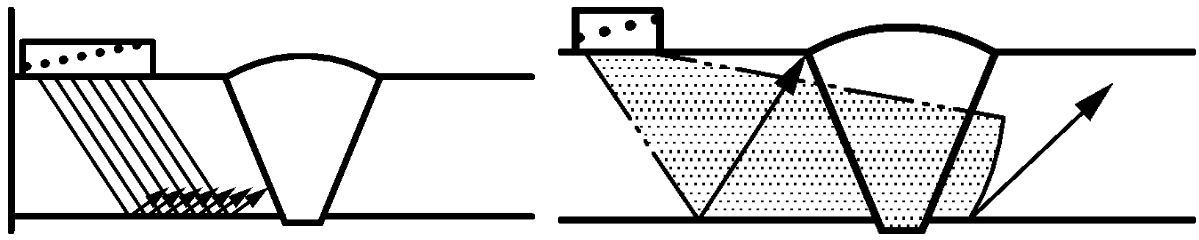


Figure 6. Scheme of electronic scanning with fixed positions of probe: linear (a), sectorial (b), according to EN ISO 13588.

The scanning speed of most automated ultrasonic systems for weld inspection is limited to 100mm / sec. It is determined by factors such as: number of delay laws, scan resolution, signal averaging, pulse repetition frequency, data acquisition frequency, and inspection volume so that satisfactory images are obtained. The missing image lines indicate that too high scanning speed has been used. A maximum of 5% of the total number of lines collected in a single image may be omitted, but there should be no adjacent lines missing.
In [11], probability of detection information is reported for discontinuities at the weld root, oriented along the radius of pipes of 12mm to 32mm thickness. There are 31 discontinuities made in the weld root of heights of 0.2mm to 7.5mm in four welded joints, with 29 discontinuities of them having dimensions of up to 4mm in height. To detect them a multichannel automated ultrasonic system for weld inspection in pipelines was used, with 5 independent tests for each discontinuity. The technique of zonal discrimination of the weld was used with TOFD and phase probes. All indications with amplitude above a set threshold were read using probe channel data giving maximum echo amplitude. The effects of different types of probes (frequency and dimensions), techniques (TOFD and phased array probes) and test equipment are not taken into account, suggesting that the application of the ASTM E1961 requirements limits these differences to some extent. The shape of discontinuities and their length dimensions are not taken into account. The results analysis shows that with an average detection probability of 90%, discontinuities are recorded in the weld root of 1.3mm height. In manual ultrasonic inspection of welded joints, reliable detection is registered of discontinuities in the root of over 3mm. Automated ultrasonic inspection appears to be a more reliable method for registering discontinuities in the weld root compared to manual ultrasonic inspection.

4.2. Pipe internal inspection

Inspections by automated ultrasonic systems to detect thinning of wall due to corrosion or erosion and cracks in the base material are carried out according to the manufacturer's specifications. Ultrasonic waves are transmitted and received by the test object in the probes, either non-contact or in an immersion mode. The non-contact method is carried out by electro-magnetic acoustic probes, and the immersion one by piezo-composite probes. When the transferred fluid is liquid, it is used as a coupling medium to transmit ultrasonic waves from the piezo-composite probe into the wall of the pipeline. The ultrasonic pulse-echo inspection technique with an automated system on pipeline is given in Figure 6 [10]. Normal probes are used to inspect wall thickness, and 45 ° probes are used to inspect radial cracks.
The scanning speed is limited to 2m/s, and in some cases when using a combination with electronic scanning it can reach up to 3m/s. In inspection for cracks, the speed is reduced by up to 50%. The scanning resolution on the axis has a scanning step of 3mm and along the pipe circumference of 8mm.

Metal loss due to corrosion can be safely registered for a depth above 0.5mm and a diameter above 20mm, with the uncertainty of result being 1mm. Radical crack is confidently recorded with a length of 30mm and in depth of 1mm. The uncertainty for determining the position along the pipeline axis is 0.2m, relative to the nearest welded joint.

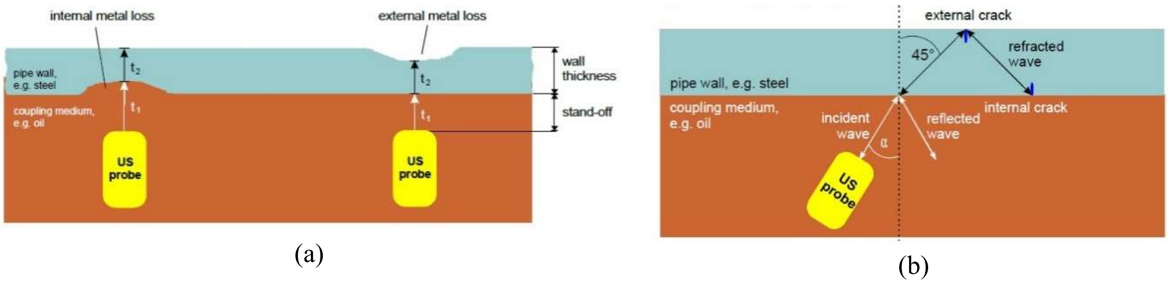


Figure 6. Applied ultrasonic pulse-echo technique to detect deviations in wall thickness (a) and cracks in the wall (b) of pipeline inspected by pipe internal automated system.

Conclusion

The following conclusions and recommendations can be made from this survey:

- For the pipe external automated ultrasonic inspection of welds, there are sufficient for the practice specifications in International and European standards for performance and evaluation of indications. While there are only company specifications for the pipe internal automated inspection, the evaluation is carried out according to International and European standards.
- The growing need for construction of gas pipelines and development of mechanized and computerized systems in the ultrasonic inspection of pipelines has increased the reliable detection of discontinuities and reduced inspection time, which has led to the replacement of the existing radiography method used in many international pipeline projects.
- In automated ultrasonic systems for pipe external inspection the mechanized head is offset during motion, resulting in false location and conditional indication size, and in some cases in loss of contact.
- Recommendation to eliminate the above mentioned shortcoming: implementation of a system for monitoring the offset from the set scanning coordinates and a system to return the mechanized head to the specified scanning coordinates, in case of possible offset; use of non-contact probes (but it should be taken into account that the sensitivity of the inspection is significantly reduced due to decrease in the signal-to-noise ratio typical for this type of probes).

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