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Automatic ultrasonic testing of girth welds in thin wall pipelines

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1. Introduction

Quality control of welding joints is necessary for building safety metal constructions, including high pressure and medium pressure pipelines. The most popular method of testing is ultrasonic testing by hand. Operator of ultrasonic setup scans the weld area with the ultrasonic share wave beam and registers parameters of detected flaws. This is time consuming and leads to some human errors.

Automatic testing is more reliable and faster because computer driven scanning system does not skip any signal received from ultrasonic probes and the software can be adjusted for the registration of specific flaw signal levels and distances as well as for appropriate testing speed. Testing results can be obtained in real time almost immediately, so the imperfections detected above the some permissible level can be corrected on the spot. Control process should not slow down the work on pipeline, like in case of radiographic inspection. This last requirement becomes a necessity.

There are some equipment of this type available now on the European market: μPIPELINE of English companies AEG-Technology and SONOMATIC, ROTOSCAN of Dutch company RTD, MIPA of German companies Gottfeld and Krautkrämer, or Czech–Polish Vizus2000. These are fully computerized mechanical systems, some of them mounted on tracks, ready to work in hard field conditions. But they are, also for economical reasons, made mostly for thick wall pipelines testing (for above 10 mm wall thickness).

Method of testing, practical solutions and application area presented in this paper are complementary to existing equipment. Trend to automated testing is straightforward today and it is forced by new technologies as well as by market demands.

Ultrasonic testing of welded joints has been developed in Poland for more than forty years and details on suggested testing procedures and on flaw evaluation methods can be found in Polish standards and in other literature [1–8]. The standards cover most of practical cases and they are still being improved to achieve uniformity in testing methods, results presentation and welding joints qualification. However, to take into account all possible real world situations inside one uniform standard system is very weak idea. As an example, automatic ultrasonic testing of welded joints is beyond industrial standards in Poland now, while the works in this area are in progress as in case of this article.

In this paper we present a method of automatic ultrasonic testing of thin wall pipe welding joints together with prototype constructions. More precisely we deal with the pipe diameter in the range of 100 to 400 mm and wall thickness up to 10 mm. There is a demand for testing this type of constructions in power plant industry and in heating systems. Progress in geothermal energy utilization in Poland during last ten years leads to new quality control requirements for pipeline networks for hot water and steam as energy transport media. They contain big amount of minerals causing fast increase of corrosion in welding joint area even with only small inner surface defects. From the analysis of girth welds testing of power plant "Turów" it is clear [5] that the reasons of 50% leakage cases were small inner surface defects of comma, circular or oval shape. Welding joints of thin wall pipes can be tested by ultrasound, often in heavy load conditions. These are mostly butt weld joints, welded from one side only. The main flaw types encountered are: spherical type flaws like simple pores or slag inclusions, elongated type flaws like concavities, lack of fusion and excessive penetration (happen often) or cracks (happen rather seldom). These types of flaws can be detected by ultrasonic method and their size can be evaluated. Their positions in welds depth cannot be measured because of using transversal wave ultrasonic probes with incident angle of 70 degrees, which beam width in flaw distance is often larger than the wall thickness. This parameter is also irrelevant because of small wall thickness. There are difficulties with flaw type evaluation. It is not a problem with small, spherical type flaws, but it is important if a long type flaw is classified as an excessive penetration or as a lack of fusion. In hand made ultrasonic testing echo height criteria is usually applied. For example, elongated flaws with echo height above the on-screen line corresponding to ϕ 1.5 mm etalon hole are classified as lack of fusion or crack and below this line as excessive penetration, concavity or weld reinforcement. It is already known from practice that besides all these problems with testing results interpretation, automatic ultrasonic testing of welding joints in thin wall tubes is worthwhile. Radiographic inspection is much more expensive and takes a lot of time. Hand made ultrasonic testing is very annoying, also time consuming, but in some cases it is the only possible method to apply to improve reliability of construction.

2. Short review of existing solutions

To show what equipment and what testing methods are used for ultrasonic girth weld inspection, two systems are shortly presented: ROTOSCAN and MIPA. They are made generally for large diameter thick wall tubes, above 10 mm wall thickness, but probably they can be also fitted to thin wall, small diameter tubes.

2.1. ROTOSCAN made by RTD, Holland

ROTOSCAN [11] is an ultrasonic testing system for welded joints in thick wall pipelines. It uses 32 channels SONOLOG equipment and multi-probe scanner moved by electric motor along the wide steel band wrapped around the tube, next to the tested weld (Fig. 1). Two sets of probes with water coupling applied are located on both sides of weld and are hold down by springs. They test different weld zones and are arranged for different flaw orientation. For longitudinally oriented flaws, transversal waves of incident angles from 55° to 75° are introduced from different distances for echo method on each side of the weld, perpendicularly to its axis. Received echo signals are selected by the time gates with delays corresponding to the weld area. Another two transversal wave probes with incident angles 65° are located on each side of weld and work in transmit-receive mode. Probes are skewed 32° to receive signal reflected from the flaws oriented transversally to the weld axis. For coupling control, echo from water-steel boundary is monitored for each probe. Calibration is made to set proper gate positions using a piece of pipe with artificial flaws created in the middle of tested zones. Computer software controls scanner movement using position encoder and processes, displays and stores testing data. Output signal from the gates is continuously displayed for each 6 probes as well as resulting C-scan and D-scan mappings

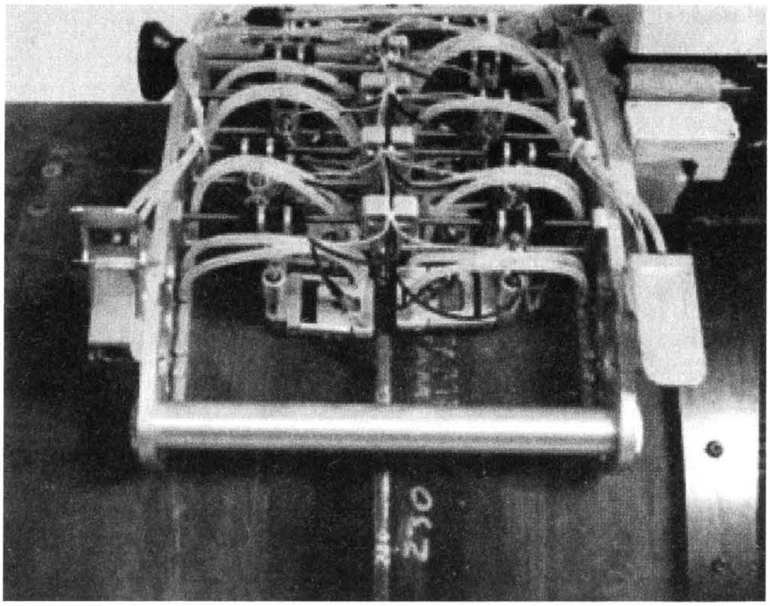


FIGURE 1. ROTOSCAN. Scanner with ultrasonic probes and water supply tubes, attached to the steel band enwrapped around the pipeline next to the tested weld.

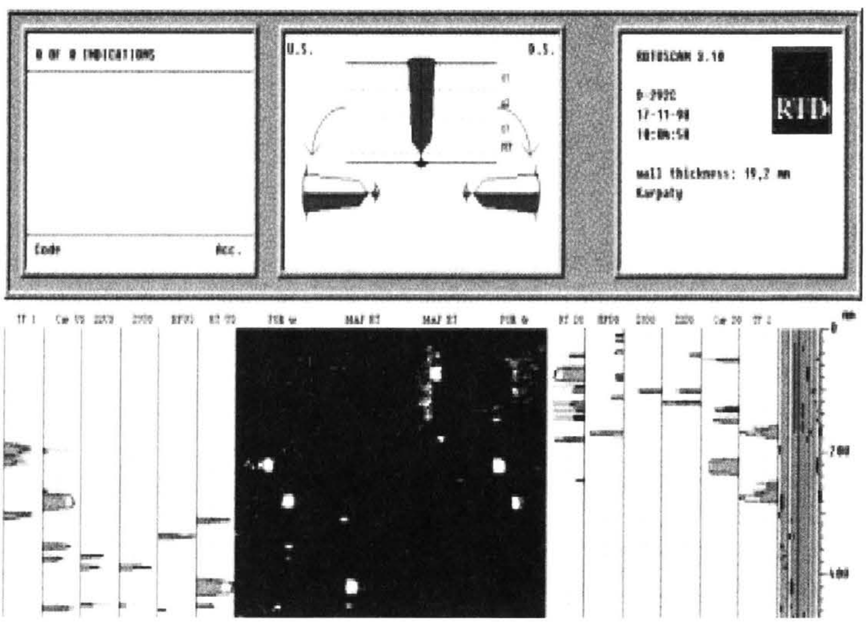


FIGURE 2. ROTOSCAN. Example of registration and visualization of test results from calibration block. For both weld sides each channel gates outputs can be seen as well as corresponding C and D scans.

for both sides of the weld (Fig. 2). Additionally, transversal flaws detection and coupling quality is registered. Number of probes in scanner varies with release version and the newest one has a set of TOFD probes added as a complementary method.

2.2. MIPA made by Gottfeld, Germany

MIPA (Multiple Immersion Probe Arrangement) system uses 16 channels USIP 20 GP16 equipment by Krautkrämer, computer controlled Extension Box and it uses two immersion probe systems located on both sides of weld [12]. Probes are moved by electric motor along the band wrapped around the tube, near the tested weld. Extension Box comprises two T/R switches, two channel boards and position encoder interface. All the probes are 5 MHz, 5 mm diameter and are located in different distances from the weld axis, 6 on each side of the weld. For four probes incidence angels in steel are adjusted on steel-water boundary to be 45° to 55° for transversal waves. Two other probes generate longitudinal waves, one near the outer wall surface and another near inner wall surface. All the waves travel perpendicularly to the weld axis and all of them work in echo mode. Calibration is made on calibration block with artificial flaws to adjust time gates positions. Computer software controls scanner movement using position encoder and processes, displays and stores testing data. Output signal from the gates

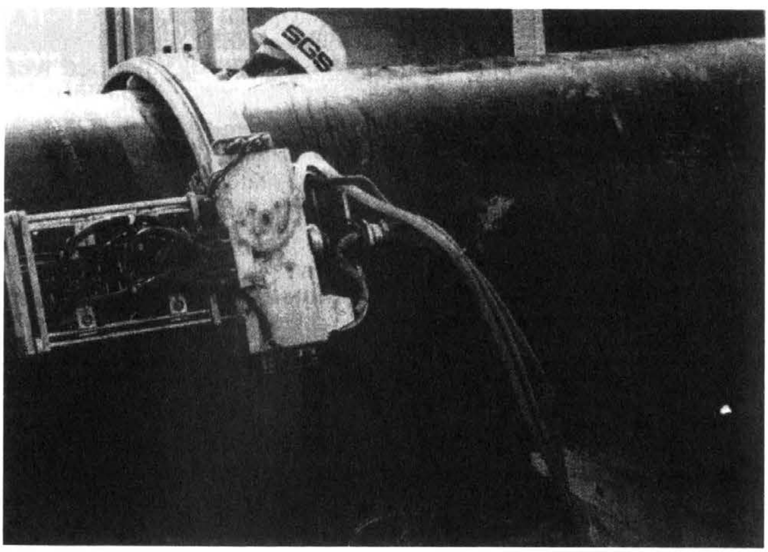


FIGURE 3. MIPA. Scanner positioned on the weld and attached to the guiding band.

is continuously displayed for each 6 probes with level encoded by color as well as resulting B-scan can be displayed for each scanner position (Fig. 4). Additionally, coupling quality is registered. Scanner speed is 36 mm/s. New scanner versions have additional set of probes for transversally oriented flaws as well as separate adjustment of each probe orientation to achieve the best sensitivity of flaw detection.

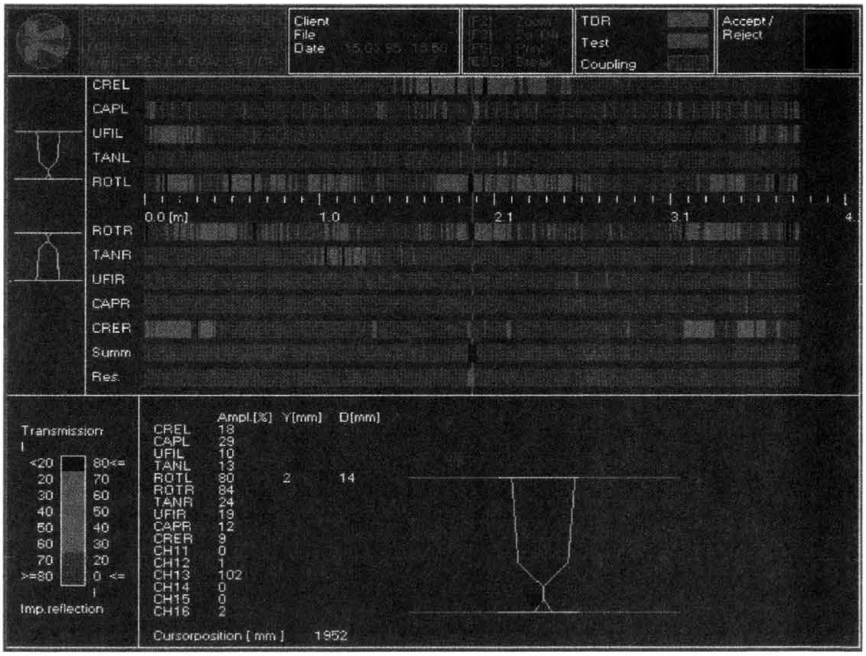


FIGURE 4. MIPA. Example picture of test results registration and visualization. Color encoded output levels from each ultrasonic channel on both sides of weld can be seen as well as B-scan cross-section.

3. Testing method, prototypes of scanners and control software

Testing method is based on two ultrasonic transversal wave angle probes located on tubes outer surface in equal distances on both sides of girth weld. Probes with incident angle of 70 degrees and with frequency 4 MHz are used (Fig. 5).

The distance between probes is defined by the beam width at the distance from weld from the 7 × 7 mm transducers and by the wall thickness. Two scanners were made, using cup grease as acoustic coupling media and using

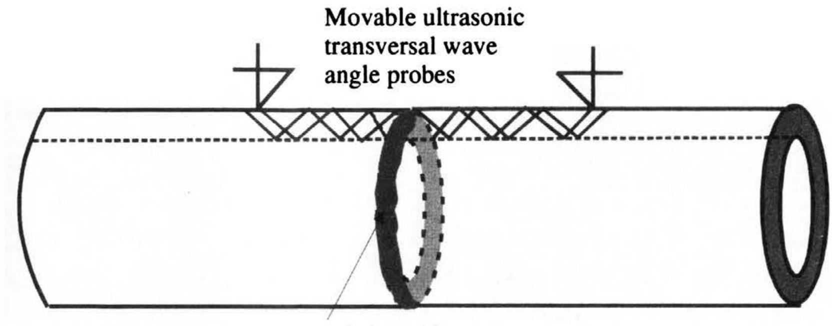


FIGURE 5. Schematic picture of automatic ultrasonic testing of girth welds in thin wall pipes.

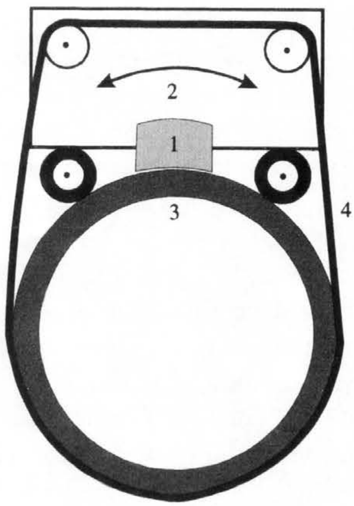


FIGURE 6. Schematic cross-section of working apparatus: 1 – one of ultrasonic probes, 2 – scanner with rubber rollers below and motor driven teeth rollers above, 3 – tube under test, 4 – rubber belt with teeth.

water (Fig. 7 and Fig. 8). In the first case, thin film of grease is put around the weld and along it before testing start. In the second case a thin film of water below both scanning probes is provided during whole testing process. The quality of solution is better depends on testing circumstances and on further technological treatment of the tested area. Grease or oil cannot be applied if the surface has to be painted. On the other hand, coupling media cannot be a factor speeding up the corrosion processes in material. Probes are moved around the tube by driving scanner on rubber rollers. It is mounted on the tube by two fasten belts. The first prototype (with grease coupling) was driven by stationary motor located on the tubes outer surface (Fig. 7). In the second prototype the scanner moves under inner, teeth shaped surface of rubber belts and is driven by its two motors (Fig. 8). This assures weld testing all around the tube (Fig. 6).

Scanner movement is controlled by software. Two probes are for 4 MHz transversal waves with incident angle of 70 degrees in steel. Surface waves can be easily generated in probes with these parameters. Welding joints in thin wall tubes have convex caps so that surface waves can be reflected from them and can give erroneous echo signals. Main beam transversal wave after few reflections from the tube walls reaches welding area and returns back reflected from the flaw. The ratio of transversal wave velocity to longitudinal wave velocity (c_T/c_L) can change from $(1/\sqrt{2})$ for the Poisson coefficient $\sigma = 0$ to 0 for $\sigma = 0.5$. From this, the surface wave velocity to transversal wave velocity ratio is in the range from 0.87 to 0.96. If the distance for transversal wave is longer than for surface wave and the surface wave velocity is smaller than transversal wave, interfering surface wave echo and transversal wave flaw echo can overlap on the screen. For this reasons probes constructed for high attenuation of surface wave should be used. Each probe in the scanner has independent mounting and holding down system to be kept close to the outer surface of tubes. Moving speed is similar for both prototypes (with grease and with water acoustical coupling, see Fig. 7 and Fig. 8) and is approximately equal to 10 m/h. Total weight of the second prototype (including two motors) is 1600 g and its dimensions do not exceed $350 \times 110 \times 60$ mm. Scanner control and acoustic signal data acquisition are made by software driving dual channel ultrasonic PC board SFT4001HPCI made by SOFRATEST, France. Compete software, including control program, dynamically linked libraries (DLLs) and hardware drivers for Windows 95/98/98SE/ME or Windows NT/2000/XP operating system has been made in ZAF PAN [9, 10, 11]. Libraries contain board driving functions as well as signal data processing functions: rectifying, averaging, filtration, rejection, and precise time-of-flight and pulse amplitude measurements. Control program gives A-scan (like in oscilloscope) display of signals received by both ultrasonic probes. However, signal from the second probe is displayed from the top of screen, downward, and with reversed time base direction. This specific solution permits to obtain (by signal delay adjustments in each channel) echo signals received from the same reflector by both probes to be displayed in the same horizontal position on the screen. Another testing results display window, maps these time base lines and marks with different colors (green and blue) for each probe when the signal amplitude exceeds the selected registration level. When the level is exceeded for both probes in the same distance area, this is marked

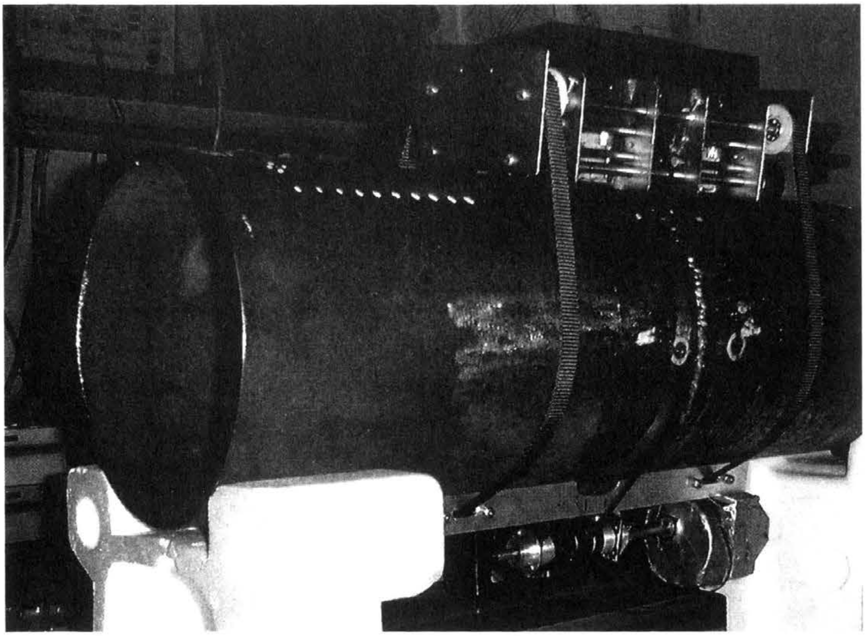


FIGURE 7. General view of girth weld scanner prototype made for cup grease as acoustic coupling.

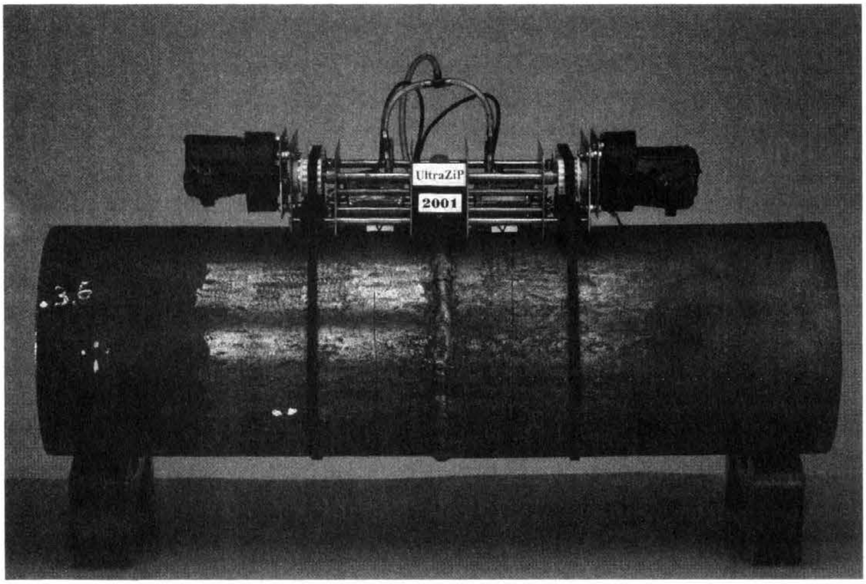


FIGURE 8. General view of girth weld scanner prototype made for water as acoustic coupling.

by red color. If the scanner moves along the weld, subsequent lines create C-scan display (view from the top) in this window. Ultrasonic probes work in echo mode one by one in each separate ultrasonic cycle and next both in transmit-receive mode for acoustic coupling quality testing. Pulses pass through the tubes wall during coupling testing period and are picked up by separate gates to mark their presence on both, left and right edges of window. Continuous (if coupling is good) vertical black lines on the window edges are generated during testing process (Fig. 9).

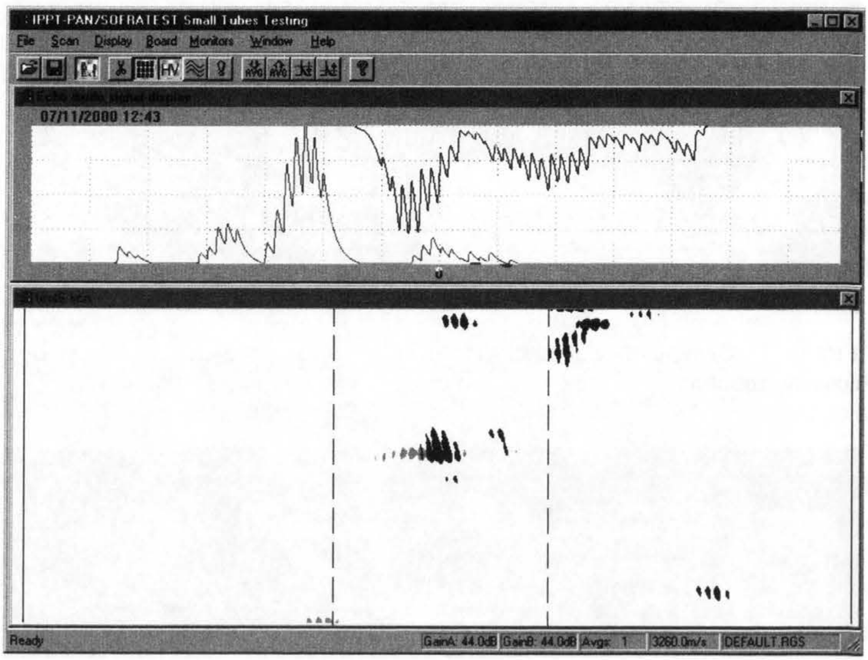
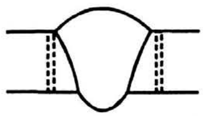
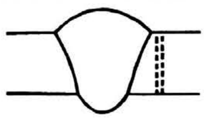
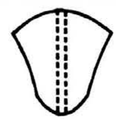
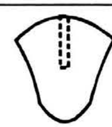
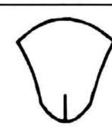


FIGURE 9. Screen view of control program for automatic ultrasonic testing of girth welds in thin wall tubes. In upper window: A-scan of ultrasonic signals from two probes. In lower window: partial C-scan along the weld axis with some signals registered separately by two probes (originally in green and blue colors) and simultaneously by both of them (red color). Broken vertical lines in the center mark the weld cap area. Vertical black lines on the edges of window show proper acoustic coupling conditions. Detected artificial flaw ($\phi = 1.0$ mm port) is mapped at the middle of window.

4. Testing results and comparisons with other methods

For laboratory measurements the sample tube of 157 mm outer diameter, 500 mm long and of 4 mm wall thickness with welded joint in its half of length has been used. Some artificial flaws have been introduced into weld area, similar to natural flaws detected earlier in power plant pipelines [5]. They have been spread in distances allowing for the detection of only single one, see Table 1.

TABLE 1. Set of artificial flaws introduced into weld area to test measurements possibilities of equipment.

No.	Flaw type	Flaw parameters	Flaw picture
1.	Two ports located symmetrically around the welding joint	Port $\phi = 0.9$ mm	
2.	Single port on one side of welding joint	Port $\phi = 0.9$ mm	
3.	Port on the weld axis	Port $\phi = 0.9$ mm	
4.	Blind hole in cap to depth of 0.5 of weld thickness	$\phi = 0.9$ mm	
5.	Notch in root, along the weld axis	Diamond disk circular saw, 0.3 mm thick, 1 mm notch depth	
6.	Notch in the root, perpendicular to weld axis (1.2 mm wide)	Notch depth 2.5 mm	

Additionally, $\phi = 0.9$, 1.0, 2.0 mm ports have been generated for the calibration purposes. Calibration of equipment is necessary for each particular tube diameter and wall thickness. Having done it, all the parameters can be stored in a file. Further corrections can be made from time to time as the mechanical parts wear and tear. For calibration, piece of tube 500 mm long with welding joint in the middle of its length and with artificial flaw ($\phi = 1.0$ mm port in this case) is proposed. After setting the scanner symmetrically around the flaw and applying acoustical coupling, adjustments to delays and gains are made in both channels to achieve the echoes from both probes in the center of signal display window. After additional scanner position corrections along the weld axis to obtain maximum amplitude for both pulses, the echoes heights are adjusted to three screen divisions by using gain controls for each channel. Scanner is now calibrated and can be moved to the tube to be tested. Examples of test results are shown in Figs. 9 and 10.

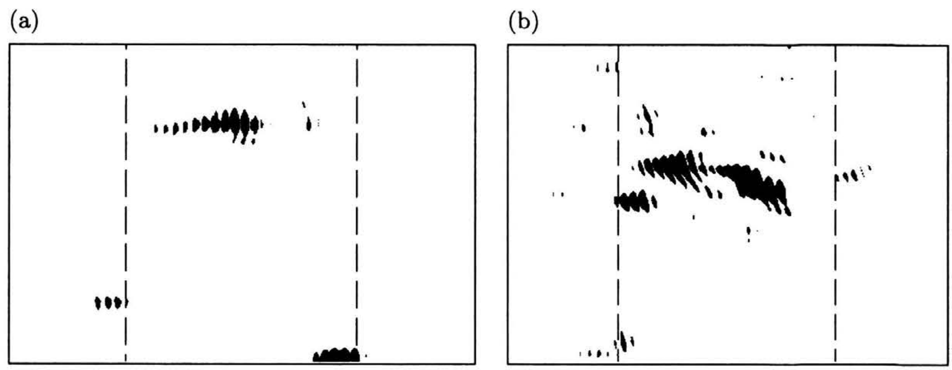


FIGURE 10. Enlarged parts of C-scan window: (a) detected ϕ=1.0 mm port artificial flaw but with scanner movement in the opposite direction than in Fig. 9, (b) natural flaw detected in weld area.

Automatic ultrasonic testing has been verified by hand made ultrasonic tests by three independent operators and by radiographic inspection. For ultrasonic hand made testing Unipan 510 apparatus has been used together with transversal wave angle probes 2T70° 10C. The sensitivity was set equal to 30 dB on the radius $r = 50$ mm of W2 calibration block. Radiographic inspection was made using Liliput 140 apparatus (made in GDR/Poland/Hungary) to burn through single wall. X-ray film has been located inside the tube, close to its inner surface. Burning was made from outside the tube, from the top, 500 mm away from the surface. For 130 kV voltage applied, burning time was set to 4.2 minutes. To obtain figures of full welding length, five radiograms have been made.

By making comparisons between ultrasonic method (including automatic testing) and radiographic inspection it was found that only artificial flaw not detected by ultrasonic methods was the notch: 1 mm wide, 3 mm deep and 5 mm long, cut in the root perpendicularly to the weld axis. Flaws of this shape and orientation are difficult to detect by this method but they are rather rare in practice. This flaw is clearly visible on the radiogram. Other artificial flaws were properly detected and evaluated by both methods.

As an example, Fig. 11 shows the comparison of radiogram and automatic ultrasonic testing results for the same area on the tube surface. Upper picture is 1:1 fragment of the radiogram, 4 cm along the weld axis, 10 cm wide, which corresponds to ultrasonic C-scan picture of the same area lower.

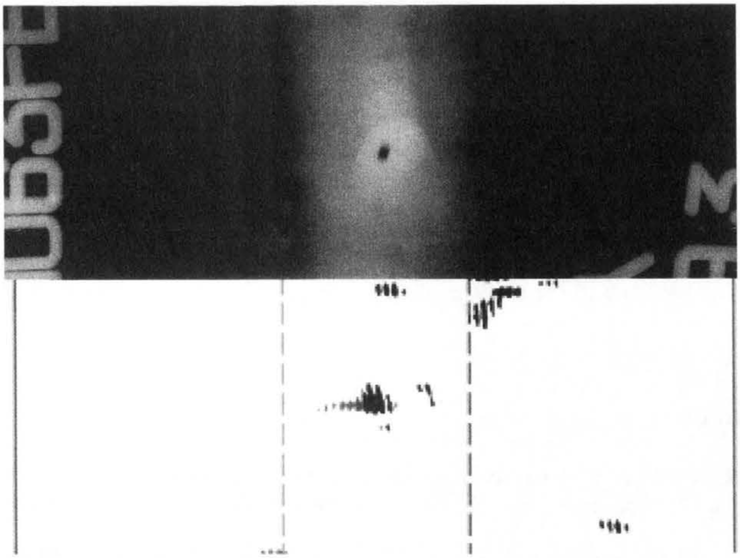


FIGURE 11. Comparison of testing results of the same area on tube surface, obtained by radiographic inspection and by automatic ultrasonic testing.

In the center part of radiogram, weld area can be seen at all picture height. Also 0.9 mm port, located 80 mm from measurement base (along the weld axis) is visible. Ultrasonic scan picture has two vertical broken lines in the center to mark weld cap position and two vertical lines on the edges to show proper acoustic coupling conditions. Echo signals above registration level generate green or blue areas while artificial flaw area is marked by red color, as detected by both probes simultaneously.

Figure 11 shows that automatic ultrasonic testing results are very intuitive and can be easily compared with radiographic inspection results. Document with test results can be obtained immediately after testing (it takes about 2 minutes on the tube with 157 mm outer diameter), is easily readable and inspection costs are lower then ultrasonic tests by hand. It is due shorter time of single weld inspection as well as due to fast, easy and convenient test results handling by computer system.

5. Conclusions

Presented prototype solutions show only tentative approach to automatic ultrasonic quality tests of thin wall pipelines. It has to be verified in field tests, preferably just after welding process, before mounting for exploitation. The necessary condition for testing during exploitation period is an access to weld areas, allowing scanner mounting and its free movement along weld axis. The described system has few advantages as well as limitations.

The advantages are:

- Automatic registration of all test data without operators engagement.
- Small weight and dimensions for easy relocation.
- Easy fitting to different tube diameter and wall thickness.

As a limitation, in comparison to hand made ultrasonic testing, one should mention inspection by the ultrasonic beam exclusively perpendicular to the weld axis.

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