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ACOUSTIC METHODS

Data-Processing Algorithms for Automatic Operation of Ultrasonic Systems with Coherent Data Processing

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Abstract—Two algorithms for the automatic determination of flaw parameters during ultrasonic testing of welded joints with a high level of structural background noises are considered. The experimental data collected in the course of automated ultrasonic testing (AUT) using Avgur series with coherent processing of data (Avgur 4.2 and Avgur 5 systems) and the results of the assessment of nondestructive testing data are used. The first algorithm is used to identify zones where flaws may be located. This algorithm is applied after running AUT in the "search" mode. If the parameters of the algorithm application are selected properly, this algorithm makes it possible to determine the coordinates and the conventional length of the identified flaws. The second processing algorithm is intended to determine the flaw's actual length and height. For its operations the algorithm uses the images obtained from coherent data processing. Results of testing methods for automatic (computer) determination of flaw parameters are cited. These results are obtained by the Avgur system during testing of austenite welded joints in stainless-steel pipes with a diameter of 325 mm and in perlite-steel pipes of various diameters.

1. INTRODUCTION

Ultrasonic (US) nondestructive testing methods are widely used in industry. Automated systems are one of the most important directions in the development of US testing. The application of such systems yields results with good objectivity of flaw identification and determination of these flaws' coordinates, conventional length, and equivalent dimensions [1, 2]. However, for experts, these data are not fully sufficient for the reliable calculation of the endurance of an object being tested. Owing to this, the systems using coherent data processing have been widely used [3, 4]. Such systems feature options for the additional determination of a flaw's actual length and height and, if required, its profile, as well as for monitoring of objects being tested [5]. This information is used, taking into account other characteristics affecting the object's durability, for the advanced calculations of a welded joint's endurance. If calculations indicate that the endurance allows the object to be used further, the welded joint can still be used in equipment; otherwise, the joint is to be repaired.

However, the automated assessment of testing results and the determination of the flaw's actual parameters encounter certain problems.

The automated collection, registration, and processing of data can be implemented successfully. At the same time, assessment of the testing results and determination of the importance of an image's details, the specific features in this image's flaw, this flaw's dimensions and location in the welded joint, etc., significantly depend on the skills of the expert conducting testing and assessing the obtained results. This task can hardly be automated because of the necessity to solve an inverse problem, i.e., to determine the type and parameters of a discontinuity using measurements of the acoustic field reflected or scattered by this discontinuity. Inverse problems are often ill-posed problems, which may have more than one solution. Because of this, it is extremely difficult to do without an expert who assesses results on the basis of certain rules and personal experience. Some indicators characterizing flaws can be formulated, formalized, and used for the development of a logical algorithm for the determination of flaw parameters. However, the final decision is nevertheless to be made by an expert.

It should be noted that the set of indicators characterizing flaws is not clearly defined, and it is not possible to "integrate" them into the logical algorithm for identification of flaws. Their use for the automated solution of the classification problems may require application of neuron network algorithms [6].

Below we consider only those algorithms that use the main and stable indicators characterizing a discontinuity, i.e., its presence, actual parameters, profile, and type (extended, not extended, filamentary, volume extended, or planar).

In order to decrease the time needed to test and optimize the data containing information on discontinuities, operations of the automated system with coherent processing of data are divided into two stages: search and measurement. Each of these stages ends with the assessment of the collected data by personnel.

The search mode is intended for the identification of flaw zones for subsequent measurements and for the determination of flaw lengths and coordinates. The measurement mode is intended for the determination of types and parameters of identified flaws.

An expert is involved in the solution of each of these problems. The determination of flaw-zone boundaries for subsequent measurements is a simpler task. Its solution does not necessitate a highly trained expert (operator) for performance of the test. However, determining the types and parameters of identified flaws is a more complicated task that requires the higher skills of an expert.

The first task can be formalized easily, and an operator does not need to spend much time on it (usually several minutes). However, this time makes up about thirty percent of the total time needed for data recording.

The second task is much more difficult to formalize and has not yet been resolved in full. An expert must spend a lot of time on this task (tens to hundreds of minutes), especially when low-quality data are used (bad contact, uneven surface, etc.). Therefore, any automation of the expert's work is very useful.

2. DETERMINATION OF FLAW ZONES

Paper [7] contains results of applying the amplitude algorithm for the automatic identification of flaw zones by the use of A-scan images during data recording by the TOFD method. The algorithm for the identification of flaw zones by the use of incoherent images of flaws in the search mode, which is used in the Avgur system, is based on the same concept. However, such an algorithm loses its efficiency during US testing of materials with a high level of structural noises (stainless steel, austenite welded joints, etc.).

The algorithm described below can be successfully used for US testing of materials with the increased level of structural noises and of regular low-noise materials.

This algorithm is applied to files containing incoherent images of the tested article's volume. These images are obtained during the search mode of the Avgur system's operation. The recorded-data file contains a set of B-type images corresponding to scanning along a welded joint at different distances by a piezoelectric probe.

Figure 1 shows a projected B-type image where all the images of this type obtained at different distances from the welded joint are displayed on the same XZ plane. Here, X (horizontal axis) is directed along the welded joint, and Z (vertical axis) sets the distance between a discontinuity and the scanning plane. The Y axis corresponds to the direction perpendicular to the welded-joint line. It characterizes the distance between the electroacoustic probe and the welded joint.

Such an image has the following specific feature: a discontinuity is displayed in it as an image "spot" located at different distances Z (with the same coordinate X), which has an increased image amplitude. However, in the majority of cases, the area of the increased noise level related to welded-joint effects behaves in the same, albeit less regular, way. Here an operator can sufficiently easily identify "dubious" zones. However, time is required for viewing the image, assessing the collected data, selecting the coordinates of the "dubious" zone, and recording of the decision to perform further measurements. The operator may also miss discontinuities of small lengths (and any height).

The algorithm for automatic identification of such "dubious" zones basically reproduces the operator's actions:

(1) For each B-type image, the low-amplitude noise is removed by threshold cutoff T at a level

$$T = A + 2\sigma,$$

where A is an average intensity of the image, and σ is its dispersion.

(2) The image is smoothed to reduce effects of external factors (changes in the acoustic contact, instabilities in the device operation, etc.). To do so, (i) the filter is sequentially shifted across the image with a one-point step, (ii) the intensities of the initial image are summed up using the filter's weighting factors, and (iii) the obtained sum is normalized by dividing by the sum of the weighting coefficients. A 3×3-pixel image with a unit intensity serves as the filter.

(3) The image obtained is projected onto the XY plane; i.e., at each point of this plane, an average amplitude along the Z axis multiplied by the number of A-scan layers is found. As a result of this procedure, it is possible to monitor the behavior of the "dubious" images when the distance between the piezoelectric probe and the welded-joint line changes.

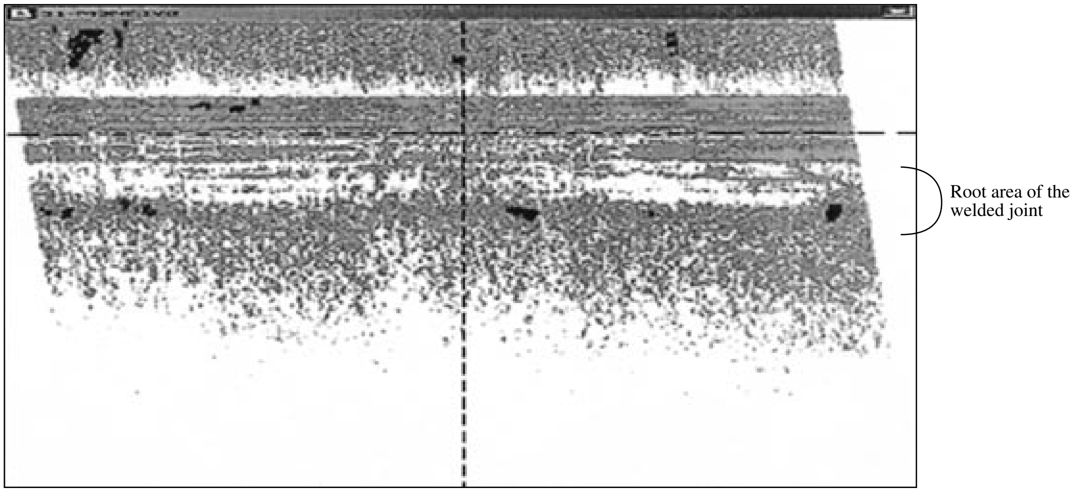

Fig. 1. Image of data on the monitor in the search mode of the Avgur 4.2 system.

(4) The procedure is concluded by creating a two-dimensional cross section of the image along the *X* axis, i.e., the dependence of the image amplitude on *X* determined for fixed values of *Y* and *Z*. The analysis of the section involves finding areas with nonzero values and combining these areas, the distance between which being less than three steps along the *X* coordinate. The areas obtained are considered “dubious” zones (Fig. 2).

The left-hand part of Fig. 2 shows a generalized and filtered projective image of the B type (in coordinates *YZ*) after the algorithm’s first through third stages have been performed. One can easily see systems of “spots” corresponding to a single *Y* coordinate, which indicate the discontinuity’s localization. The right-hand part of Fig. 2 shows a graphical image of the cross section of the generalized filtered image obtained as a result of performing the algorithm’s fourth stage. In the upper part of the window, the numerical values of the beginning and end of the “dubious” zones are displayed.

The results of applying the described algorithm are displayed in the form of an Excel table (Fig. 3) containing coordinates for the beginning and end of the “dubious” zone and the maximum amplitude of the image inside the zone. At the same time, these zones are “marked” in the corresponding files. These zones are then inspected in the measurement mode.

The algorithm’s operational integrity was tested on welded joints of perlite-steel pipes with diameters of 1020 and 828 mm and of stainless-steel pipes with a diameter of 325 mm.

The identification of “dubious” zones through the use of software and through the determination of zone boundaries by an expert are compared below:

(1) The algorithm for obtaining data using the program works equally well for pipes of different diameters.

(2) The zones identified by the program contain all the discontinuities identified by experts.

(3) The comparison of the results obtained by means of an expert’s analysis and by the program shows that, in many cases, the program fails to find zones identified by an expert. However, following the measurement testing, additional expert analysis confirmed that flaws were absent in all of these zones.

(4) The total length of the program zones intended for measurement testing is almost 30% less than that of the zones selected by an expert. Thus, the program permits a significant reduction in the time needed for measurement testing.

The program for the search of flaw zones is used for the automatic determination of measurement-testing areas by the Avgur 5.2 system.

When setting the threshold values for the amplitudes of signals from flaws, even under conditions of a high level of structural noises, it is possible to automatically determine the conventional parameters of flaws using an absolute criterion.

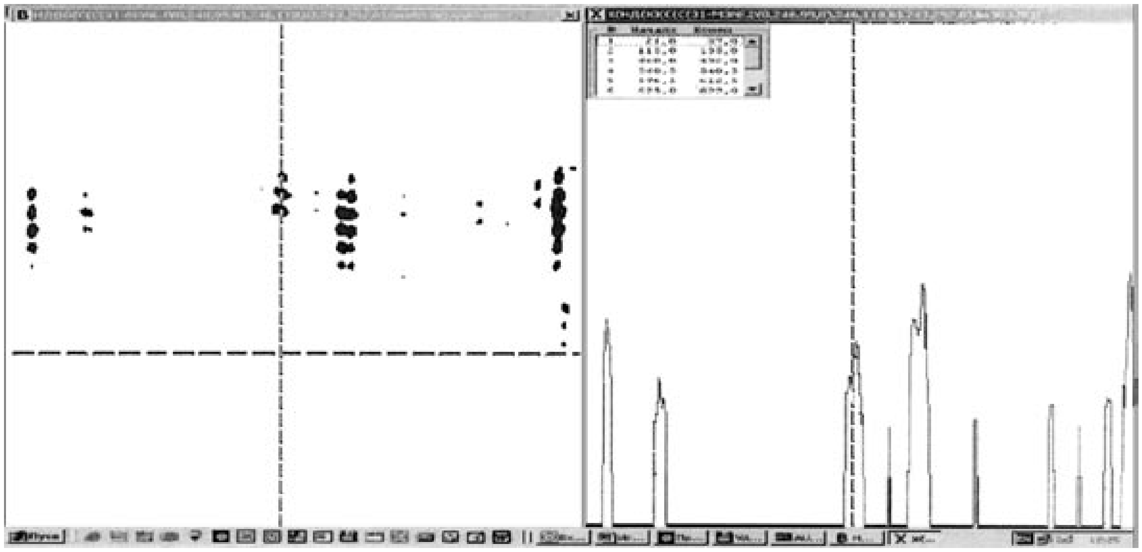

Fig. 2. Results of the algorithm's application.

3. AUTOMATED DETERMINATION OF FLAW PARAMETERS

As it was noted above, as a result of the automatic determination of flaw zones using the amplitude algorithms, flaws are identified and their conventional lengths are determined. However, when the actual length and height of a flaw are measured, additional analysis carried out by an expert is needed. Below we describe an algorithm designed to determine actual parameters of flaws (length and height). It should be stressed that the results obtained using this algorithm should be analyzed additionally by an expert. At the same time, the amount of the expert's routine work needed for assessing control results is significantly reduced owing to (i) the identification of the flaw, (ii) the elimination of such types of analysis as the determination of coordinates of each of the image's parts, and (iii) automatic logging of data.

A specific feature of the algorithm is that it operates efficiently under conditions of increased structural noise of a material, e.g., when testing austenite welded joints in 325-mm-diameter stainless-steel pipes.

The algorithm for determining discontinuity flaws uses files with images of the tested article's volume. These files are obtained from coherent processing of data collected during the measurement mode of the Avgur system.

A representative image of the object being tested, i.e., a welded joint with a weld deposit, resulting from coherent data processing is shown in Fig. 4.

This figure contains images of the B type (with coordinates X, Y_k = 629.4 mm, and Z) and the D type (with coordinates X_m = 24.6 mm, Y, and Z) of an extended flaw located on the interface between the welded joint and base metal. It also contains a scheme of the welded-joint bevel according to the design documentation. The X and Y axes are directed perpendicular to and parallel to the welded joint, respectively, and the Z coordinate determines the flaw's depth with respect to the pipe's outer surface. The weld-deposit area features an increased level of the structural noise.

Figure 4 also displays the problems to be taken into account during the process of automatic determination of flaw parameters: the presence of structural noises and the unstable quality of the acoustic contact that arise during scanning along the welded joint owing to significant rippling of the surface in the zone close to the welded joint.

The algorithm for automating actual parameters of flaws involves several stages: (1) preliminary processing of images; (2) identification of the set of image elements associated with discontinuities against the noise background; (3) determination of discontinuity type; and (4) determination of the contour of the flaw and of its parameters.

First Stage. Preliminary Processing of Images

This processing procedure comprises (i) cutting off low- and high-amplitude noises in the image, (ii) searching for local maxima across the entire B-type image, and (iii) determining the contours with the

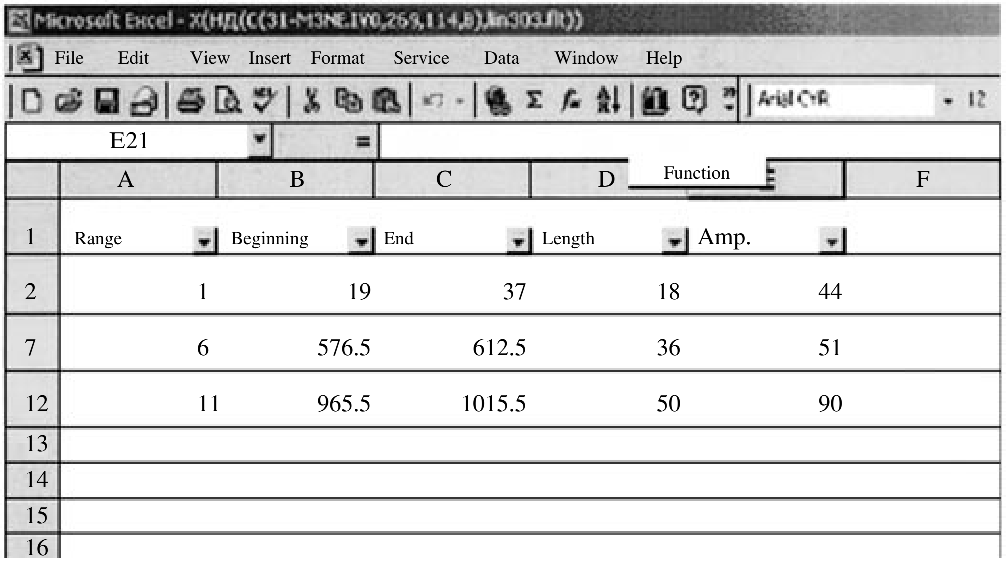

Fig. 3. Results of the algorithm's application for the search of "flaw" zones.

same intensity around each local maximum. The processing procedure is intended to describe the analyzed image by a small set of indicators.

The low-amplitude noise is cut off using the same procedure that is applied in the algorithm for determining flaw zones. The high-amplitude noise related to cross talk, pulse interference, and other artifacts is removed by filtering the image using filter S. This filter is a two-dimensional weight matrix

$$Sk \equiv Sxz,$$

which determines the image of an obtained pointlike source through use of a corresponding piezoelectric probe with the cutoff at a level of 0.5. Since the filter's size is significantly smaller than the size of the image to which this filter is applied, all image details with characteristic dimensions less than the resolution-element size will be smoothed and larger details will not be affected. The new value of the matrix of intensities at point j is then given by the expression

$$\tilde{A}_j = \frac{\sum_{k \in S} S_k A_k}{\sum_{k \in S} S_k},$$

where point j corresponds to the geometric center of filter S. The result of this operation is assigned to the filter's central point.

Thus, the filtering procedure consists of (i) sequential shifts of the filter across the image by one point, (ii) summing intensities of the original image with the filter's weighting factors, and (iii) normalization of the obtained sum by the total of the weighting coefficients.

Figure 5 shows the result of filtering the image of a flaw in the welded joint of a stainless-steel pipe. The acoustic situation in such articles features a high level of structural noises both in the area of the welded joint itself and in the area close to it where the flaw being considered is localized. One can see easily that the image obtained from such processing is "cleaned" to a significant extent from noises of a different nature. This allows dealing with a comparatively small number of local maxima, which may correspond to the localization of the reflecting area, and with two-dimensional contours associated with them.

Then, for each plane generating the filtered image of the B type (the XZ plane), local maxima are searched for.

To do so, the two-dimensional matrix of filter weights S is considered as a mask that determines which points falling within the filter's aperture are taken into account in calculations. If the geometric center of the filtering mask is located at point j, these image points will be considered as neighbors of the point to which nonzero values correspond in matrix S. When the intensity of the image at given point j is larger than or

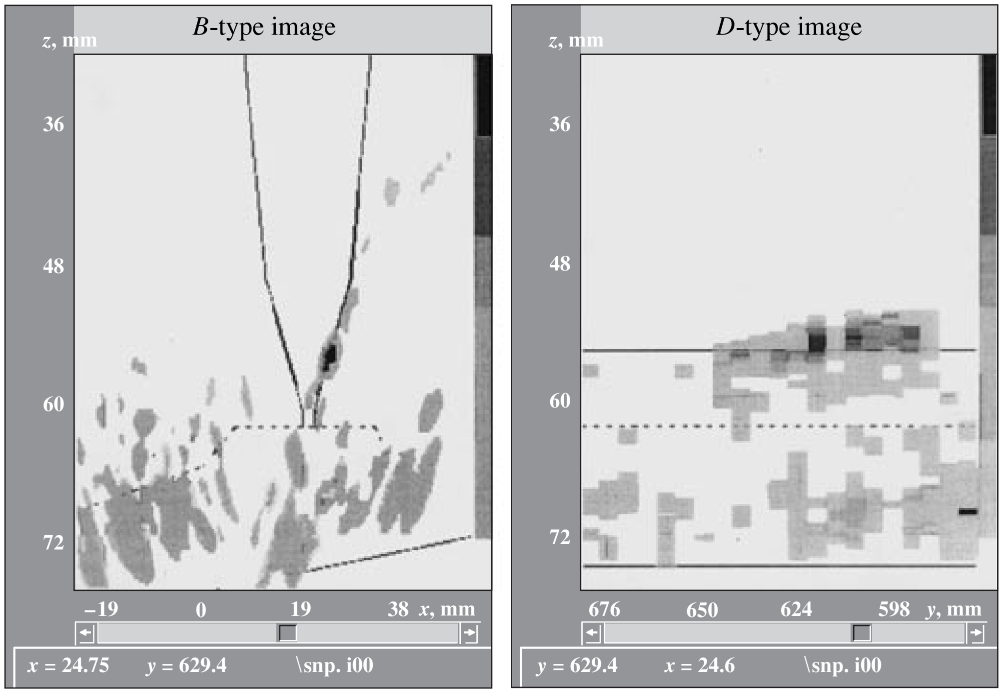

Fig. 4. Images of an extended flaw. *B*-type (left) and *D*-type (right) images. Solid lines correspond to the welded-joint bevel.

equal to the image's intensity at all of its neighboring points, this point is considered a local maximum in the image's intensity field. Then the intensity of the image at such a point remains unchanged. If at least one point from among the neighboring points is found where the intensity is larger than that at point j, point j is not a maximum according to the definition given above, and the intensity at this point is set to zero.

Two-dimensional contours are constructed for each maximum in the given plane with an intensity equal to that of the image at the point with the coordinates of the local maximum multiplied by a specified relative level (for example, 0.7 of the maximum value).

Second Stage. Identification of the Set of Image Elements Associated with Discontinuities on the Noise Background

Further processing is based on the implementation of a set of logical rules that determine the set of image elements related to a discontinuity. It is assumed that two-dimensional contours can be associated with the following discontinuities if they meet the rules described below.

The size of each contour should be no less than 50% of the resolution element's dimension (along the X and Z axes). Note that this requirement is met almost always, but when a contour does not meet this requirement it is considered "dubious" and should be analyzed by an expert.

The contours located in adjacent planes (along the Y axis), where the difference between the coordinates of maxima is less than half the resolution element for X and Z, are aggregated. It is possible that contours in the adjacent first and second layers (in each direction) are missed due to the possible loss of the acoustical contact in the process of recording data. As a result, three-dimensional contours are created, the elements of which belong to the same discontinuity. The determination of three-dimensional contours essentially solves the problem of identifying the discontinuity elements in the volume of the welded-joint area subjected to ultrasonic testing.

Figure 6 shows an example of how the algorithm for identifying discontinuity elements operates for a flaw in the welded joint of an 830-mm-diameter pipe with a weld deposit. One can see full-fledged three-dimensional contours that are displayed as a "skeleton" line passing through local maxima of the three-dimensional image of the tested object. The contours associated with a discontinuity that are identified from expert analysis (1) satisfactorily agree with the data obtained using the program (2). According to ultrasonic data, contour *3* corresponds to inhomogeneity at the interface between the welded joint and the base metal; contour *4*, to the interface between the welded joint and the austenite weld deposit.

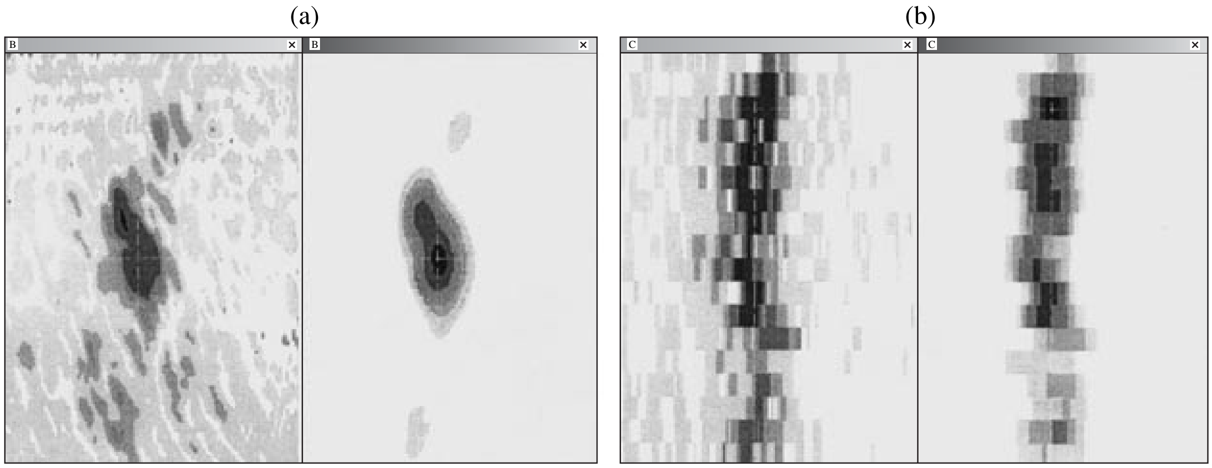

Fig. 5. Images of a flaw in a welded joint (left) before processing and (right) after cutting off low- and high-amplitude noise: (a) *B*-type image and (b) *C*-type image.

Third Stage. Determination of the Discontinuity Type

To determine the discontinuity type, all possible pairs of three-dimensional contours are considered. The algorithm distinguishes the following discontinuities: nonextended, extended, volumetric, planar, and filamentary.

A discontinuity is considered nonextended when the length of the three-dimensional contour is less than the distance between three adjacent planes (along the Y axis). Chains of individual nonextended discontinuities are observed as well. In this case, individual discontinuities should be located at a distance that exceeds the distance between three adjacent planes.

A discontinuity is considered extended when the length of the three-dimensional contour exceeds the distance between three adjacent planes.

A discontinuity is considered planar if there is a pair of three-dimensional contours that meets the following requirements:

the number of B cuts, where the contours belonging to both of the considered three-dimensional contours are observed, is less than four;

on each XZ cut, the angle between the line connecting the maxima of the corresponding contours and the Z axis is not greater than 45°;

the two three-dimensional contours being considered are collinear with an accuracy of ±15°.

A discontinuity is considered filamentary when it belongs to the extended type but consists of individual three-dimensional contours or of a chain of such contours. The height of the corresponding discontinuity is usually less than 3 mm.

A volumetric discontinuity features a high amplitude of the flaw image. This is mainly because the scattering indicatrix for such flaws is other than zero in a broad range of angles.

Fourth Stage. Determination of the Contour of the Flaw and of Its Parameters

After the three-dimensional contours have been determined, it is comparatively easy to identify the flaw contours and parameters. There is, however, a problem related to the fact that not all of the contours identified by the program can be associated with a discontinuity.

First, the presence of geometric reflectors related to the specific features of the design of the tested volume yields high-amplitude reflected signals and results in the emergence of three-dimensional contours after the completion of the second stage of image processing. Such contours can be automatically filtered if accurate information about the geometry of the welded joint being tested is available. However, the actual profile of a welded joint does not accurately correspond to its design documentation. Therefore, to filter out such contours, it is necessary to use the skills and experience of an expert or adaptive self-learning algorithms that implement fuzzy logic or neuron networks.

Second, the interface between two media with different wave impedances always generates a reflected signal, which is often observed in the image of the cross section being tested and identified by the program as a three-dimensional contour. Such a situation is shown, for example, in Fig. 6 (contours *3* and *4*). The

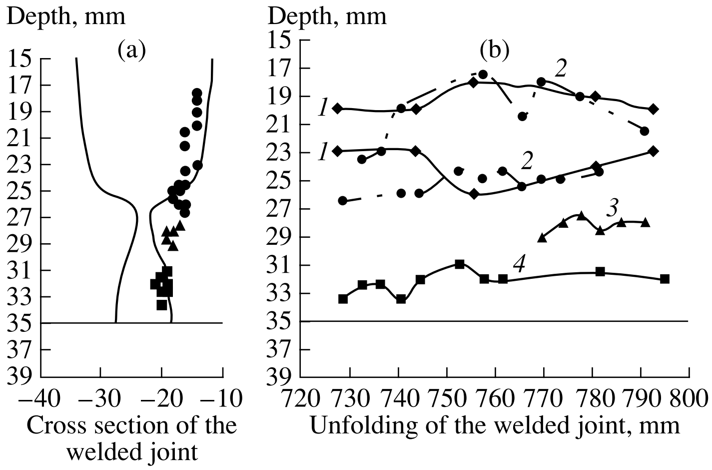

Fig. 6. Elements of discontinuities found after performing the second stage of the algorithm: (a) corresponds to the projection of the maxima of all contours of the identified discontinuity on the *XZ* plane (plane of the transversal cut in the welded joint) and (b) corresponds to the projection of the maxima of all contours of the identified discontinuity on the *YZ* plane (plane of the cut along the welded joint). Here, the idealized bevel of the welded joint is also shown (solid lines): *1* corresponds to the contours of the flaw found on the basis on an expert's analysis; *2* corresponds to the contours of the flaw found using the program code; *3* corresponds to the contour of the boundary between the welded joint and the base metal; *4* corresponds to the contour of the boundary between the welded joint and the weld deposit found using the program code.

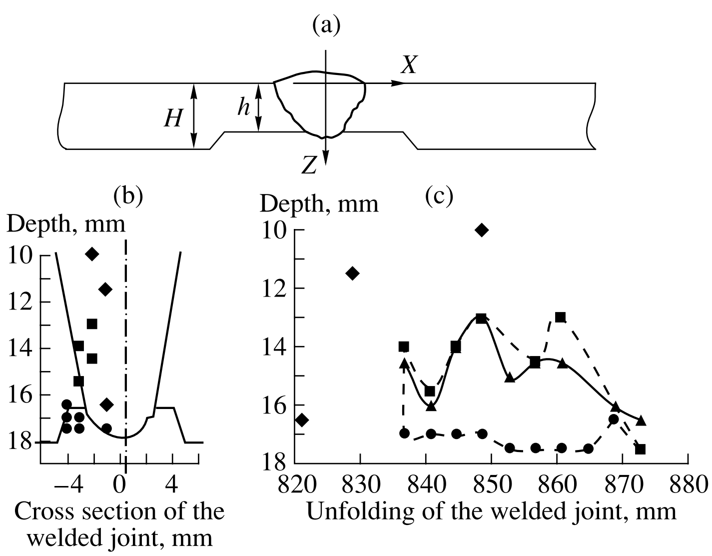

Fig. 7. Results of the automated determination of the profile of a planar discontinuity in the welded joint in a pipeline: (◆) corresponds to "dubious points," (▲) corresponds to points identified by an expert, (■) corresponds to the points on the flaw's upper edge identified using the program, and (●) corresponds to the points on the flaw's lower edge identified using the program.

amplitude of images associated with such contours is usually significantly smaller that of the contours corresponding to discontinuities. This rule is, however, frequently violated. Hence, when determining parameters of a flaw and its contour in the tested volume, it is very useful to have a priori information about the prevailing character of flaws (subsurface or surface flaws, etc.). A number of logical rules can then be formulated, making it possible to determine contours of flaws and their parameters.

We have formulated these rules for corrosion flaws in austenite welded joints in stainless-steel pipes with a diameter of 325 mm. In these articles, planar surface flaws prevail, which develop from the pipe's inner surface and are oriented along the interface between the weld metal and base metal.

In the event when the third stage of the algorithm determines that a discontinuity is of the planar type, the following assumptions are made for determining its contour:

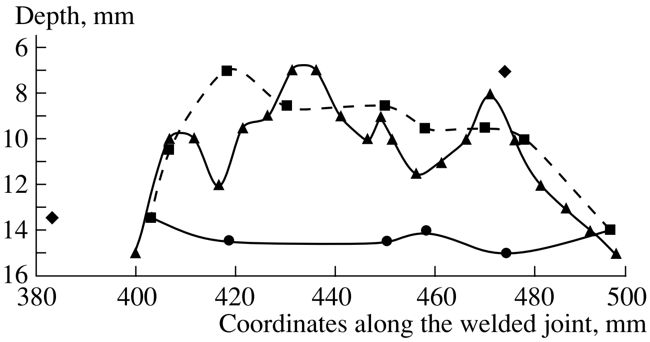

Fig. 8. Profile of a flaw in the welded joint: (i) (broken lines) as identified by the program code on the basis of the data yielded by the Avgur system; (ii) (solid line) as identified by the destructive test using the three-point bend method (rupture).

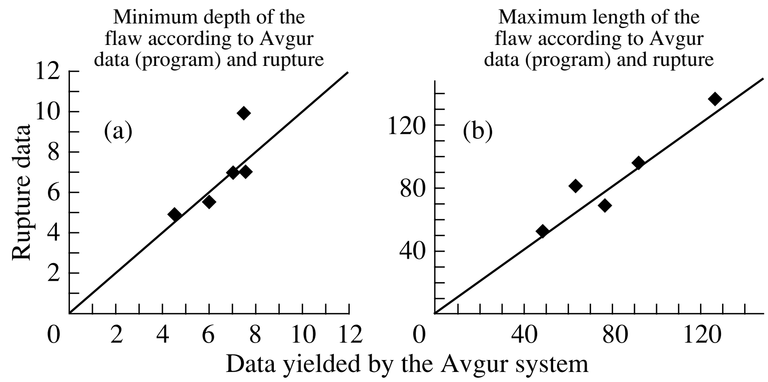

Fig. 9. Data of the measurement of the maximum depth and maximum length of defects obtained using the destructive test and using the program for processing data collected using the Avgur system.

if all points of the three-dimensional contour have a coordinate Z satisfying the inequality $h - 1$ mm $\leq Z \leq H$, the contour is considered to be associated with the discontinuity's "bottom"; and

if all points of the three-dimensional contour have a coordinate Z satisfying the inequality $Z < h - 1$ mm, the contour is considered to be associated with the discontinuity's "top."

If some of the contour points satisfy one equality and some another inequality, it is considered that the contour may belong to both the "bottom" and the "top" of the discontinuity ("mixed" type). The actual belonging of such a contour's points should be eventually determined by an expert.

Figure 7*a* shows the scheme of a welded joint whose parameters (h and H) are used in the logical algorithm being considered, and Fig. 7*b* is a projective image of the welded joint's transversal cross section. Here, all points identified by the program in the area of the welded joint with a length of 60 mm (Y coordinates of the unfolded welded joint range from 820 to 880 mm) are projected onto the welded joint's cross section. Circles and squares correspond to a planar flaw identified by the algorithm for determining flaw parameters (circles correspond to its lower edge and squares to the upper edge). Diamonds denote "dubious" points that satisfy only a part of the logical rules. Belonging of these points to the discontinuity may only be determined by an expert. In this case, none of the points belong to the discontinuity being considered. The number of such "dubious" points is usually not large; however, they should be analyzed by an expert because they may contain points belonging to a flaw.

Figure 7*c* shows a projection of the longitudinal section of the welded joint. This is actually the flaw's profile. Here, the points obtained using the program are connected by a broken line. Triangles connected by a solid line are the points belonging to the discontinuity's upper boundary according to an expert's assessment. Note that the error in the expert's determination of flaw parameters in this object is ±1.5 mm at a confidence level of 95% [8]. Therefore, one can conclude that the data obtained by using the program and from the expert's assessment coincide with a good accuracy. It is necessary to take into account that the data can be compared correctly for the same Y coordinates, i.e., along the welded joint.

In a similar way, we have compared the results of the calculations made using the described program with the measurements of the flaw's profile after a destructive test that uses a three-point bend (rupture). These data are shown in Fig. 8 as triangles connected by a solid line.

Here, as in Fig. 7, "dubious points" are shown separately (as diamonds). When analyzing data the expert decided to take into account one of these points (Y coordinate = 472 mm). As a whole, data of nondestructive and destructive tests agree with each other rather well. Here, the points connected by a broken line are found using the program. Similar to Fig. 7, squares correspond to the upper boundary of the discontinuity and circles to its lower boundary.

It should be noted that, when strength calculations are made, information about the flaw's maximum length and height is used [9, 10], while in monitoring of welded joints, it is important to know the flaw's profile because such information enables one to monitor the flaw-development process and to make timely corrective actions [10].

The measurements of the maximum length and height of flaws obtained by means of the destructive test and computer processing of nondestructive-testing data yielded comparable values (Fig. 9).

4. CONCLUSIONS

(1) We have considered algorithms for automating different operation modes of the automated system with coherent data processing. These algorithms are intended for automatic processing of the results obtained in tests of articles with high levels of structural noises. When testing such materials as, e.g., perlite-class steels with a normal signal-to-structural noise ratio, the considered algorithms will undoubtedly yield even more stable results.

(2) Tests of the algorithm for the automatic identification of flaw zones during the process of search inspection of pipelines with various diameters have shown its high efficiency. The algorithm is implemented as an option in the software for the Avgur 4.2 system. It is also integrated in the software for the Avgur 5 system, thus making it possible to automatically select measurement-inspection zones (expert zones) and record data in those zones, i.e., without the operator's interference. When algorithm parameters are configured properly, it is also possible to automatically determine the coordinates and the conventional length of a flaw.

(3) The tests of the algorithm for the determination of discontinuity parameters have shown that this algorithm allows one to determine the coordinates, type (extended, nonextended, volumetric, planar), length, and height of a discontinuity. Availability of a priori information on the prevailing characters of flaws in an article and their localization makes is possible to determine the flaw's contour. Results of the test of this algorithm in the process of testing welded joints in pipelines with high levels of structural noises are cited.

(4) The algorithm for determining the flaw parameters does not replace experts. It is intended to aid an expert in carrying out the quantitative assessment of the discontinuity parameters. It can also be used as a "counselor" when assessing data; the decision on the presence of a discontinuity and on its quantitative characteristics is made by an expert.

REFERENCES

1. Syrkin, M.M., Improving Reliability of Automated Ultrasonic Testing, *Defektoskopiya*, 2003, no. 3, pp. 11–23 [*Rus. J. of Nondestructive Testing* (Engl. Transl.), 2003, vol. 39, no. 2, p. 94].
2. Moreno, R.M., Automatic Ultrasonic System—Nuclear and Conventional Applications, *NDTnet*, 2003, vol. 8, no. 3.
3. Badalyan, V.G. and Vopilkin, A.Kh., Computer Systems for Ultrasonic Nondestructive Testing, *Defektoskopiya*, 1993, no. 5, pp. 7–13.
4. Schlengermann, U., Determination of Crack Depth Using Ultrasonics—An Overlook, *NDTnet*, 1997, vol. 2, no. 5.
5. Badalyan, V.G. and Vopilkin, A.Kh., Experience of Applying the Avgur Ultrasonic System with Coherent Data Processing on Russian Atomic Power Plants, *Kontrol'. Diagnostika*, 2000, no. 9, pp. 35–39.
6. Hassoun, M.H., *Fundamentals of Artificial Neural Networks*, Cambridge–Massachusetts–London: MIT Press, 1995.
7. Lawson, Sh., Recent Developments for Automatic On-Line TOFD Inspection, *NDTnet*, 1997, vol. 2, no. 9.
8. Badalyan, V.G., Error in Measurements of Flaws Using Systems with Coherent Data Processing, *Defektoskopiya*, 2003, no. 3, pp. 12–23 [*Rus. J. of Nondestructive Testing* (Engl. Transl.), 2003, vol. 39, no. 3, p. 179].
9. *ASME: Boiler and Pressure Vessel Code. Section 11. Rules for In-Service Inspection of Nuclear Power Plant Components*.
10. *RD EO 0489–03: Design Procedure and Standards for Allowable Flaw Sizes in Du300 KMPTs RBMK Pipeline Welded Joints*, 2003.