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SCIENTIFIC AND METHODOLOGICAL FOUNDATIONS OF PROCESSING MEASUREMENT INFORMATION ON THE GEOMETRIC CHARACTERISTICS OF FIREARM BARREL BORES

An approach to the technical diagnostics of firearm barrel bores based on determining their geometric characteristics is considered. The approach relies on the use of laser triangulation methods and tools. The form and features of presenting measurement information generated from the results of laser scanning of the barrel bore are described.

A method for processing measurement information on the geometric characteristics of firearm barrel bores is proposed, which ensures automated determination of the type, dimensions, and spatial location of barrel bore defects. A detailed description of the key operations of the method and the specifics of its application for the technical diagnostics of smoothbore and rifled barrels is provided.

Keywords: *barrel bore, technical diagnostics, technical condition, barrel bore defect, geometric characteristics, information processing method.*

Statement of the problem. In modern high-precision firearm systems, particularly in foreign-made artillery, the barrel is the primary component subject to damage. The service life of a weapon system is largely determined by the service life of its barrel. Poor-quality maintenance, increased firing intensity, and the use of substandard ammunition may lead to the premature attainment of the barrel’s limit state (before the exhaustion of its designated service life). This may also be indirectly facilitated by improper maintenance of logbooks for individual weapon systems.

The degradation process of the barrel bore (BB) is accompanied by a reduction in the projectile muzzle velocity [1], deterioration of firing accuracy, and in some cases even barrel failure. In order to prevent such situations, regulatory documents and operating manuals (for example, [2] and [3]) provide for the categorization and rejection of barrels based on the detection of the presence, type, and size of defects, regardless of whether their designated service life in terms of time or number of fired rounds ("round count") has been exhausted.

The implementation of this approach imposes high requirements on the reliability of monitoring the technical condition of the barrel bore and on the quality of its technical diagnosis (TD) [4].

Among the known methods of technical diagnosis of the BB, the method based on determining the geometric characteristics of the BB is distinguished by significant advantages [5]. It is based on the use of laser triangulation methods and an integrated set of tools and provides high efficiency and informational content, which makes it more effective compared to traditional methods of BB technical diagnosis that rely on mechanical and optical measurement principles [6].

The use of a laser triangulation measurement system involves two stages of the diagnosis process: scanning of the barrel bore and subsequent processing of the acquired data [5].

At the first stage, the surface of the barrel bore is scanned using a laser triangulation measuring device with predefined longitudinal (axial) and angular steps, and the bore radius is measured at specified points. This makes it possible to obtain an array of barrel bore radius values, which is presented either as a description of the bore surface itself in a cylindrical coordinate system or as a description of the surface of its unwrapped representation in a Cartesian coordinate system.

The second stage involves automated processing of the measurement information obtained at the previous stage, based on the results of which a conclusion is formed regarding the type, dimensions, and location of defects present on the barrel bore surface.

Despite the existence of certain theoretically substantiated models and principles for processing

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measurement information on the geometric characteristics of firearm barrel bores [7], to date there is no comprehensive solution in the form of a method that can be algorithmized and, as a result, enables automated determination of the type, size, and location of defects on the barrel bore surface based on data obtained using a laser triangulation measuring device.

Analysis of recent research and publications. Issues related to the description and investigation of methods for processing information on the geometric characteristics of barrel bores have been addressed in several domestic and international studies.

Papers [5] and [8] consider the general principles of measuring the geometric characteristics of barrel bores using the laser triangulation method, describe the design and optical layout of a laser triangulation sensor, as well as certain features of its integration into a measurement system. However, in these publications the processing of measurement information is mainly focused on solving the problem of three-dimensional reconstruction of the contour structure of the barrel bore and involves subsequent visual analysis of three-dimensional surface models, while the issue of quantitative analysis of the geometric parameters of the barrel bore is not addressed.

In studies [9–12], the application of machine learning models – specifically convolutional neural networks – to problems of technical diagnosis of surfaces, including barrel bores, is investigated. The authors mainly focus on the process of defect classification on surfaces, while the issues of determining defect dimensions and localization are not addressed.

The very approach of applying neural networks in the process of technical diagnosis of barrel bores has a number of limitations: high dependence on the quality of the training dataset, predominant orientation toward a two-dimensional input data space, and significant sensitivity to noise points. Consequently, even modern architectures of convolutional neural networks do not provide sufficient accuracy and adequacy in the analysis of defects in the barrel bores of firearms.

The analysis of the reviewed publications has shown that in most of them there is either no description or only a brief description of the methods and approaches for processing measurement information on the geometric characteristics of barrel bores that would be capable of enabling automated defect identification and determination of their key parameters.

The purpose of the article is to develop a method for processing measurement information on the geometric characteristics of firearm barrel bores that enables automated determination of the type, dimensions, and location of defects on their surface.

Summary of the main material. Scanning a firearm barrel bore using a laser triangulation measuring device provides information on its geometric characteristics in the form of a radius matrix. In the method proposed in this article for processing measurement information on the geometric characteristics of barrel bores (the method), two such matrices are used: matrix R_d, which represents the actual state of the barrel bore surface being currently subjected to technical diagnosis and is formed during its laser scanning, and matrix R_e, which represents the reference state of a barrel bore surface of this type and is either provided by the barrel manufacturer or formed based on the scanning of a new, unused barrel. Processing these matrices using the proposed method makes it possible to determine the presence, spatial location, dimensions, and types of defects on the barrel bore surface.

Before applying the method, all input information in the form of barrel bore radius values must be converted to a single system of measurement units. This is necessary because manufacturers of the structural components of laser measuring devices may specify linear dimensions in different units and presentation formats.

To simplify the algorithmization of the method, each type of defect from a pre-defined list of K defects characteristic of the corresponding type of barrel bore is assigned a conditional number in advance. For a smooth bore, this number is denoted as t_s, and for a rifled bore, as t_r. The numbering of typical barrel bore defects used throughout this article is presented in Tables 1 and 2.

It should be noted that the wear dynamics of the lands and adjacent grooves in the chamber area of a rifled bore are associated with the formation and progression of another defect – the increase in the volume of the chamber. Therefore, this article considers only the first of these defects, while the description of their interrelationship is beyond the scope of this study.

Table 1 – Types of Defects in Smooth Barrel Bores and Their Corresponding Numbers

D	1	2	3	4
Defect Type	Diametral Wear	Swelling	Crack	Pit

Table 2 – Types of Defects in Rifled Barrel Bores and Their Corresponding Numbers

Defect Type Number, t_r	1	2	3	4	5
Defect Type	Wear of the lands and adjacent edges of the rifling	Swelling	Crack	Pit	Chipping of the rifling land

The sequence of operations of the method differs for the cases of technical diagnosis of rifled and smooth barrel bores. Separate processing of measurement information is also provided for the middle, chamber, and muzzle sections of the barrel bore, since the shapes of defects and the rejection criteria for these sections differ.

The surfaces representing the unwrapped views of the specified barrel bore sections are presented in a Cartesian coordinate system, in which the *X*-axis is oriented parallel to the longitudinal axis of the barrel bore, the *Y*-axis is directed perpendicular to the *X*-axis in the plane of the unwrapped surface, and the *Z*-axis is orthogonal to the *XOY* plane and corresponds to the normal to any point on the barrel bore surface in the original (cylindrical) coordinate system.

It should be noted that some groups of operations are performed repeatedly during the implementation of the method. Therefore, for convenience, prior to the overall description of the method, it is expedient to single out a set of operations that ensure identification of the defect type and to combine them into a single generalized operation *ident(arg),* where the operand *arg* is the radius matrix *R* describing a surface area with a real defect whose type must be determined.

This operation also uses matrices Q_k, which are interpreted as surface areas modeled for the *k*-th defect type from the available set of *K* possible types. The matrices Q_k are formed using the operation $Z_k(arg)$, where *arg* is a mathematical model of the *k*-th defect type from the predefined list of *K* typical defects, and the radius matrix *R* [7].

The identification operation *ident* is performed by applying predefined criteria to a principal indicator that characterizes the degree of discrepancy between the elements of the matrix *R* and the corresponding matrices Q_k [13]. The defect number t_s or t_r (from their predefined list) is determined as k if the value of the principal indicator obtained when comparing Q_k and *R* satisfies the criterion of belonging to this defect type.

If several defect types simultaneously satisfy the criterion based on the principal indicator, additional indicators and their corresponding criteria are applied sequentially. In this case, the decision is made based on the first additional indicator that demonstrates compliance with the established criterion. If the value of the first additional indicator does not meet any criterion from the predefined list, the procedure proceeds to the next additional indicator. The order of application of additional indicators and their criteria, as well as the possible assignment of weighting coefficients, may be determined based on the results of trial operation of the diagnosis system by the barrel manufacturer (weapon system manufacturer) or by an authorized organization of the weapon system operator.

Thus, because of applying the *ident* operation, the number t_s (t_r) corresponding to the defect type on the surface reconstructed from the matrix *R* is obtained.

1. Features of Method Implementation During Technical Diagnosis of Smooth Barrel Bores

1.1. Subtraction of matrix R_e from matrix R_d is performed to determine element-wise deviations between the measured radius values of a new barrel bore (with nominal parameter values) and those of a worn barrel bore. The result of this subtraction is the deviation matrix R^{*}_{dif}, each element of which represents the change in radius at the corresponding point on the barrel bore surface.

The geometric meaning of this matrix lies in reconstructing a surface that represents the areas of the barrel bore surface that have been worn or partially destroyed (with loss of a certain volume of material) during operation, as shown in its unwrapped representation.

1.2. At this stage, it becomes possible to determine the diametral wear of the examined section of the barrel bore and assign the barrel to one of the specified technical-condition categories in accordance with the requirements of the regulatory documentation. In this case, the criteria for assessing the technical condition with respect to this defect take into account not only the absolute value of the diametral wear, but also the relative size of the surface area on which the diametral wear is observed, corresponding to the established permissible values for the given technical-condition category.

For this purpose, based on the dimensions of the examined barrel-bore section (width and length) and the maximum defect depth a_D (which in this case corresponds to the arithmetic mean calculated for a certain fraction of matrix R^{*}_{dif} elements with the highest values within a specific part of the section – for example, for the 30% of the largest elements in the barrel-bore area adjacent to the forcing cone), a diametral-wear mathematical model M_1 is used to form matrix Q_1 (the indices of the mathematical model M_k and matrix Q_k correspond to the ordinal number k of the diametral-wear defect).

Applying the approach proposed in the article for defect identification to matrices R^{*}_{dif} and Q_1, it is determined whether the shape of the barrel-bore surface section described by matrix R^{*}_{dif} corresponds to the diametral-wear model for the respective part of the barrel bore. If the conclusion is positive, the value a_D is accepted as the diametral-wear value and is used in accordance with the barrel-bore categorization procedure. Additionally, information on the detection of diametral wear in the barrel-bore section and its geometric parameters is entered into the summary table *T*, which is used to store the data required for further determination of the technical condition of the barrel bore. If the conclusion is negative, the process proceeds to the next stage.

1.3. To detect and isolate other defects on the examined barrel-bore surface (apart from diametral wear), it is necessary to eliminate the influence of such diametral wear on the results of subsequent transformations, indicator calculations, and the application of evaluation criteria. This can be achieved by subtracting the elements of matrix Q_1 from the corresponding elements of matrix R^{*}_{dif}. As a result of this subtraction, matrix R^{**}_{dif} is obtained.

1.4. Matrix R^{**}_{dif} is subjected to additional processing using the operation *denoise(arg)*, where the argument *arg* is the matrix R^{**}_{dif} itself. This is necessary due to the possible presence of minor corrosion marks and scratches on the surface. For this purpose, the elements of R^{**}_{dif} (which are, in fact, the ordinates of the points on the examined surface section) whose absolute values do not exceed a predefined threshold χ are set to zero. The value χ thus acts as a threshold within which the surface roughness of the barrel bore and other insignificant random deviations of the point ordinates are neglected.

As a result, matrix R_{dif} is obtained, representing, in a certain sense, a smoothed surface with local defects (pits, cracks, etc.) protruding above the conditional reference (zero) plane, and corresponding to the non-zero elements of this matrix.

1.5. For the subsequent determination of the sizes, spatial location, and type of defects on the surface represented by matrix $R_{dif,}$ the points belonging to individual defects are grouped (clustered) using the clustering operation *clast(arg)*, where the operand *arg* is matrix R_{dif}. A classical approach to solving this problem is the use of the DBSCAN algorithm, which determines the affiliation of points to specific surface regions based on their being located at small Euclidean distances from one another [14]. Such regions are interpreted as locally dense areas of the coordinate space that may correspond to individual defects of the barrel bore. Points lying within these locally dense regions are considered core points.

The DBSCAN algorithm has two main parameters: the neighborhood radius ε and the minimum number of points *min_samples*. If the ε-neighborhood of a given point contains at least *min_samples* points, that point is considered a core point. Core points whose mutual distances do not exceed ε are grouped by the algorithm into the same cluster.

The operation of the algorithm begins with selecting an arbitrary point. For this point, all points located at a distance not greater than ε are determined. If the number of such points is smaller than *min_samples*, the current point is marked as noise, i.e., as an element that does not belong to any cluster and may correspond to an isolated or random deviation. If the number of neighboring points exceeds *min_samples*, the selected point is declared a core point and is assigned the label of a new cluster.

Next, all of its neighbors are examined sequentially: if they do not yet belong to any other cluster, they are assigned to the current one; if they are also core points, the algorithm recursively expands the cluster by checking their neighborhoods. Cluster expansion continues until no unprocessed core points remain within the ε-neighborhood. After that, the algorithm proceeds to the next point that has not yet been examined and repeats the procedure until all surface points with non-zero values in matrix R_{dif} have been processed [15].

After the clustering operation is completed, a separate coordinate array is formed for each detected local defect, containing only the points belonging to that specific defect. The method then provides for the individual processing of each such defect, represented in the form of matrix R_u (where index u corresponds to the ordinal number of the matrix from the total number U of matrices obtained during clustering), which is fully compatible in dimensions with matrix R_{dif}. In this matrix, only those elements corresponding to the coordinates of the points of a particular defect have non-zero values: the column and row indices define the x and y coordinates of a point, while the value of the corresponding element represents the z coordinate, i.e., the depth of the local damage.

This approach is equivalent to unfolding the base of each defect onto a flat surface of the same size as the scanned section of the barrel bore, which enables further analysis.

1.6. At this stage, the operation *params(arg)* is introduced, which determines the geometric characteristics of each defect represented by matrix R_u, where R_u is the operand *arg* of this operation. In particular, the maximum defect depth a_D is calculated as the extreme value among the non-zero elements of the matrix. Next, the base length L and base width W are determined, corresponding to the dimensions of the minimal bounding rectangle that encloses all points forming the base of the defect. The rotation angle α of the base is also computed, characterizing the orientation of the defect's longitudinal axis relative to the X -axis within the range from 0 to π. In addition, the displacement of the base center relative to the X- and Y-axes, x_Δ and y_Δ, is established.

1.7. Based on the geometric characteristics determined at the previous stage and using the defect-identification mechanism described in the article, the type of the defect represented by matrix R_u is established.

1.8. The obtained information regarding the location, geometric dimensions, and the identified type of the defect is entered into the summary table T.

1.9. If, at stage 1.7, a bulging-type defect is identified on the surface represented by matrix R_u, then, after entering the corresponding data into table T, compensation of this defect is performed. Compensation is carried out by subtracting matrix Q_2, which models the bulging in accordance with its mathematical model, from matrix R_u. The resulting new matrix R_{u-dif} represents the surface with defects that may form within the bulging zone. Subsequently, R_{u-dif} is subjected to repeated processing in accordance with stages 1.5–1.8.

A flowchart illustrating the principle of applying the method during the technical diagnosis of smooth barrel bores is presented in Figure 1.

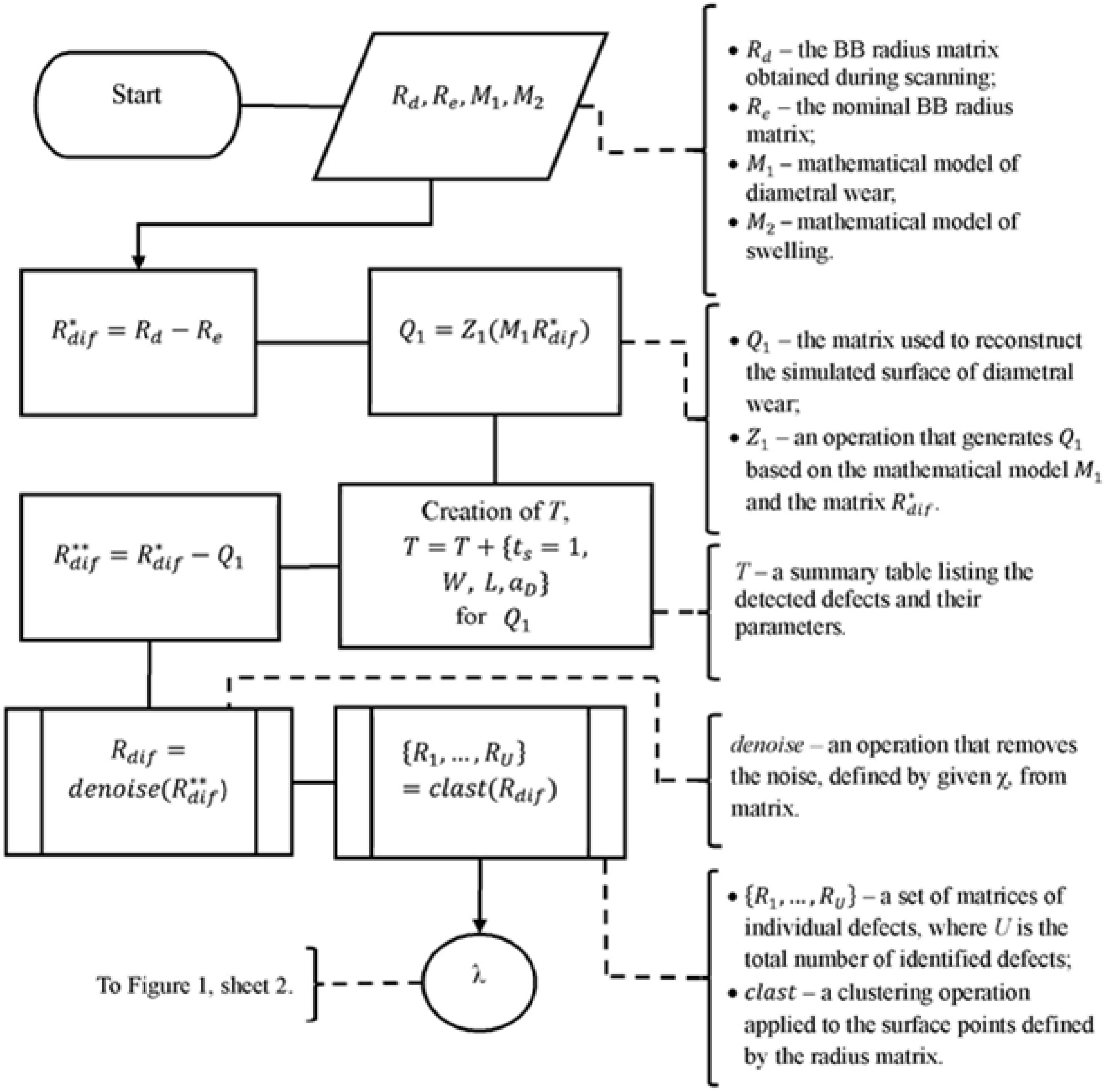
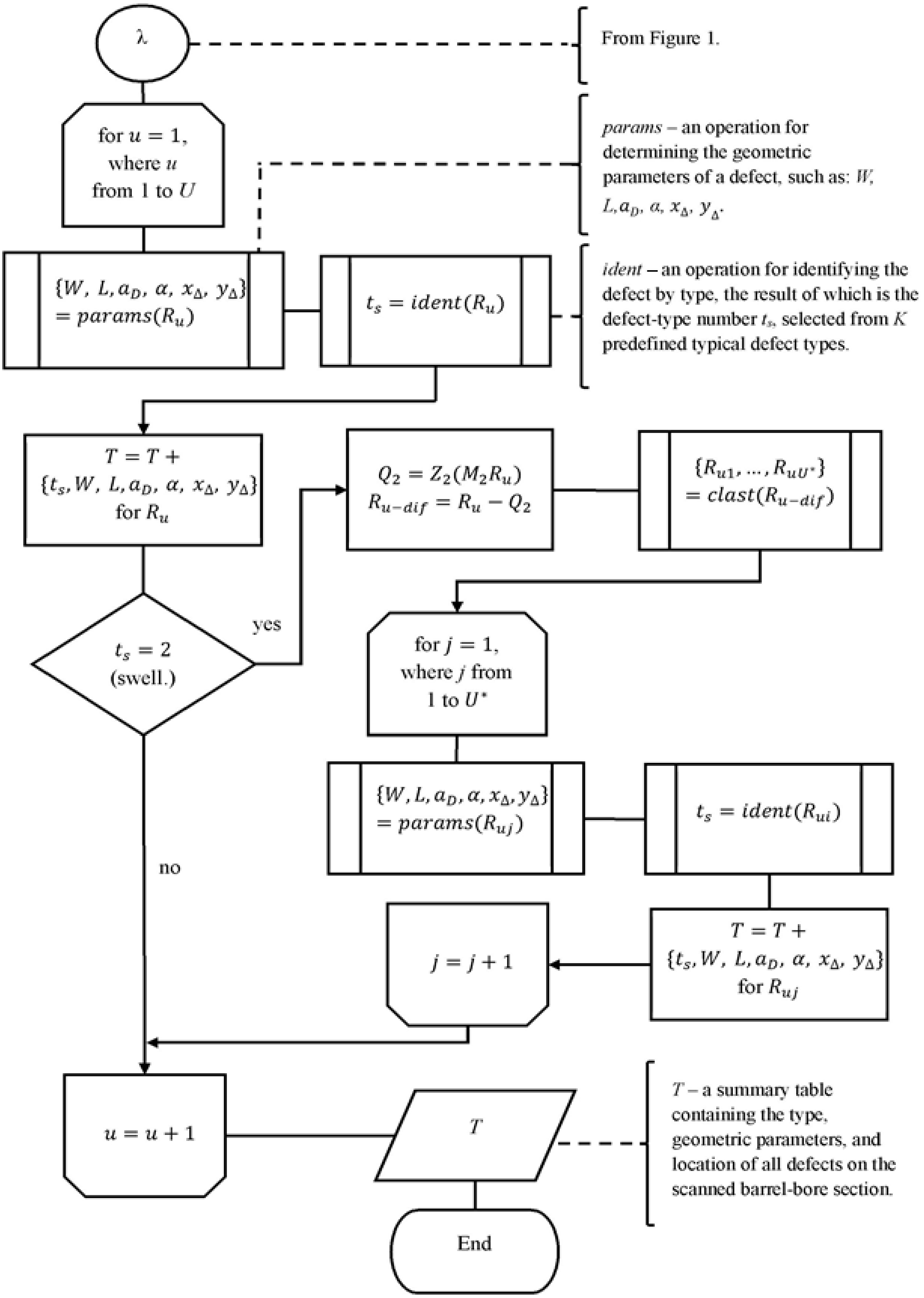


Figure 1 – Flowchart illustrating the principle of applying the method during the technical diagnosis of smooth barrel bores



From Figure 1.

params – an operation for determining the geometric parameters of a defect, such as: W, L, a_D, α, x_Δ, y_Δ.

ident – an operation for identifying the defect by type, the result of which is the defect-type number t_s, selected from K predefined typical defect types.

T – a summary table containing the type, geometric parameters, and location of all defects on the scanned barrel-bore section.

Figure 1, sheet 2

2. Features of implementing the method during the technical diagnosis of rifled barrel bores

2.1. The first stage of the method applied during the technical diagnosis of a rifled barrel bore is analogous to the first stage used for the technical diagnosis of a smooth barrel bore and involves forming the deviation matrix R^{*}_{dif} by subtracting the radius matrix of a new barrel bore R_e from the radius matrix of the examined barrel bore R_d.

2.2. The obtained matrix R^{*}_{dif} is subjected to additional processing using the *denoise* operation (stage 1.4), which sets to zero those matrix elements that are interpreted as shallow defects (scratches, minor corrosion marks, etc.). As a result, matrix R^{**}_{dif} is formed.

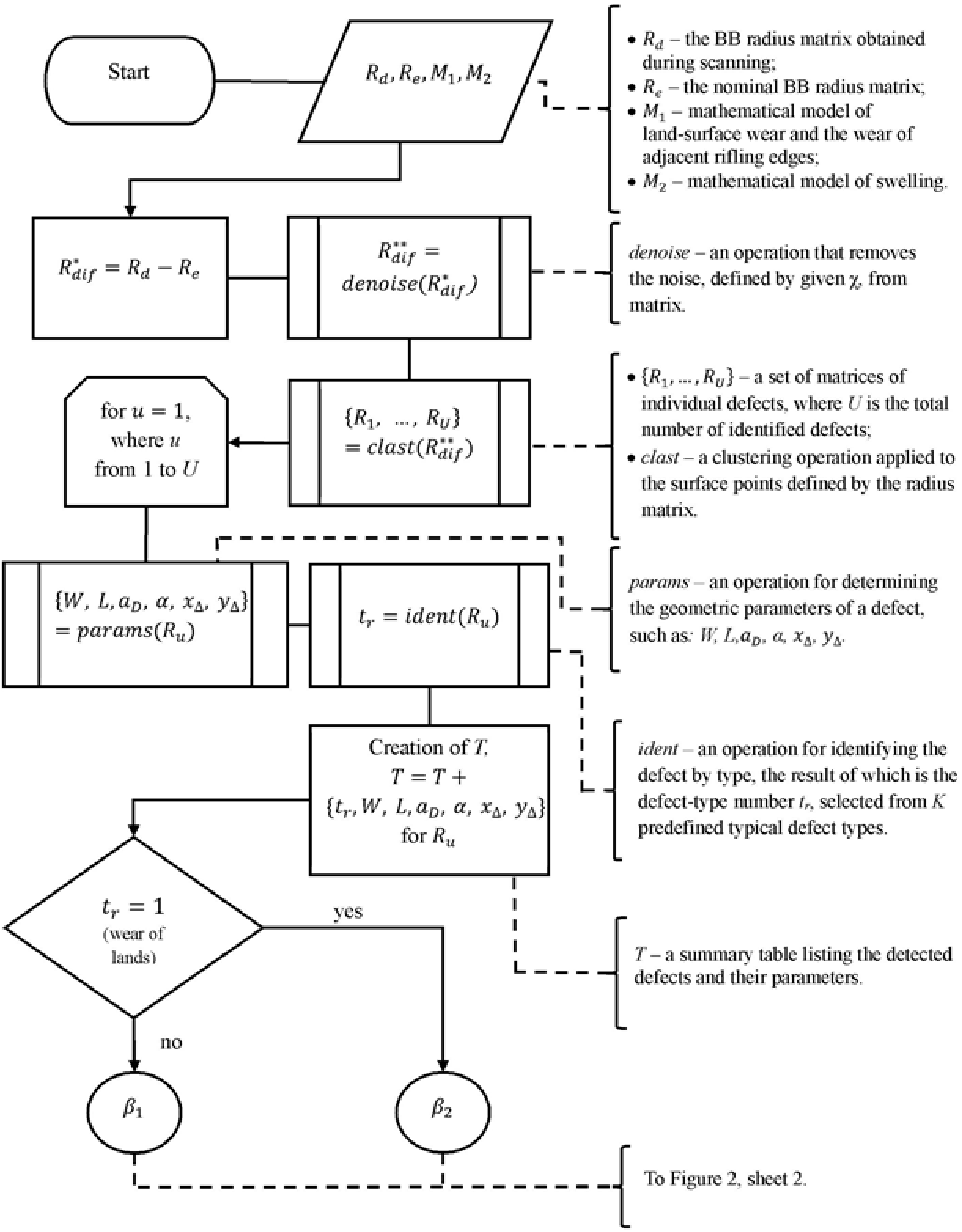
2.3. The barrel-bore section represented by matrix R^{**}_{dif} is examined for the presence of land-top wear and wear of the adjacent groove edges. This defect manifests itself as bands inclined to the *X*-axis at an angle corresponding to the rifling twist angle. If such bands are present, the *x*, *y*, *z* coordinates of the points marking their beginning and end are determined. Based on these coordinates, the degree of land-top wear is established, and, in accordance with the mathematical model of land-top and adjacent flank wear, matrix Q_1 is formed. If no such bands are detected, the procedure proceeds to stage 2.5 of this sequence of operations.

2.4. To isolate other defects on matrix R^{**}_{dif} (apart from land-top and adjacent flank wear), it is necessary to eliminate the influence of this type of wear on the results of subsequent transformations, indicator calculations, and the application of evaluation criteria. For this purpose, the elements of matrix R^{**}_{dif} are subtracted from the corresponding elements of matrix Q_1, resulting in matrix R^{***}_{dif}. The *denoise* operation is then applied to the obtained matrix R^{***}_{dif}, producing matrix R_{dif}.

2.5. By applying the clustering operation *clast* (stage 1.5), the points on the surface represented by matrix R_{dif} (or by matrix R^{**}_{dif} in the case of transitioning from stage 2.3 directly to stage 2.5) are grouped into clusters corresponding to individual defects. As a result, matrices R_u are formed, each describing a single defect whose surface protrudes above the conditional reference plane *XOY*. The obtained matrices R_u are subsequently processed individually in accordance with stages 1.6–1.9.

A flowchart illustrating the principle of applying the method during the technical diagnosis of rifled barrel bores is presented in Figure 2.

Thus, as a result of applying the described operations of the method intended for the technical diagnosis of smooth and rifled barrel bores, a summary table *T* is obtained. This table contains information on the type, dimensions, and location of all defects on the surface of the examined barrel bore. The data from this table are subsequently used in calculating the indicators required for categorizing barrels in accordance with the criteria set out in current instructions or other regulatory documents governing the assessment of the technical condition of barrels of a given weapon type. In addition, the obtained information may serve as input data for predicting the remaining service life of the barrel bore and for studying the influence of loading conditions and firing regimes on this service life.



- R_d – the BB radius matrix obtained during scanning;
- R_e – the nominal BB radius matrix;
- M_1 – mathematical model of land-surface wear and the wear of adjacent rifling edges;
- M_2 – mathematical model of swelling.

denoise – an operation that removes the noise, defined by given χ, from matrix.

- $\{R_1, \dots, R_U\}$ – a set of matrices of individual defects, where U is the total number of identified defects;
- *clast* – a clustering operation applied to the surface points defined by the radius matrix.

params – an operation for determining the geometric parameters of a defect, such as: W, L, a_D, α, x_Δ, y_Δ.

ident – an operation for identifying the defect by type, the result of which is the defect-type number t_r, selected from K predefined typical defect types.

T – a summary table listing the detected defects and their parameters.

To Figure 2, sheet 2.

Figure 2 – Flowchart illustrating the principle of applying the method during the technical diagnosis of rifled barrel bores

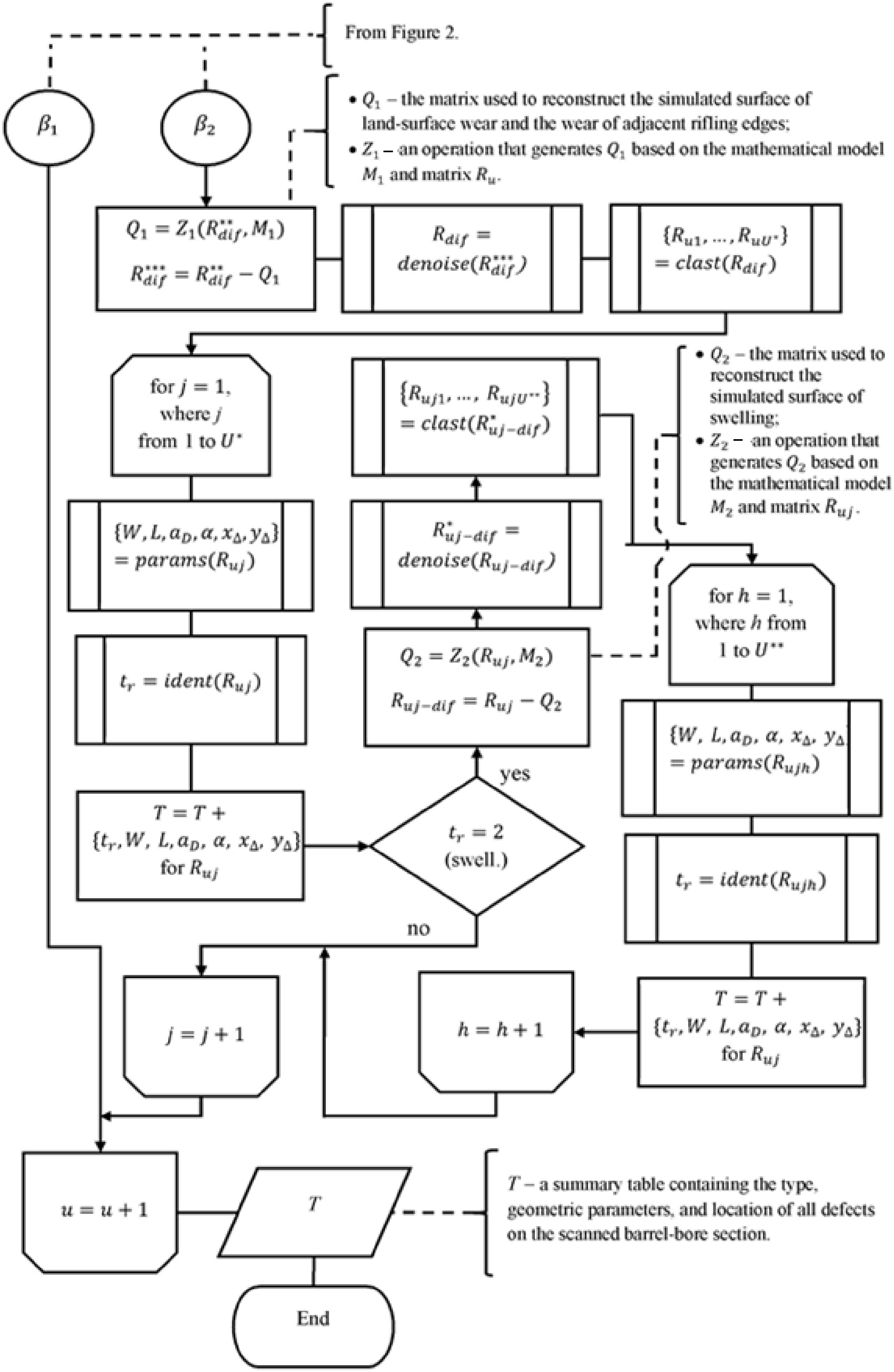


Figure 2, sheet 2

Conclusions

The method for processing measurement data on the geometric characteristics of firearm barrel bores, as presented in the article, enables automated detection of defects on the barrel-bore surface, identification of their type, and determination of their location and dimensions.

The identification of the defect type is achieved by applying criteria to an indicator that characterizes the degree of discrepancy between the geometric characteristics of the barrel-bore section containing the real defect and the corresponding characteristics of the model of a defect of a given type, where the model represents a surface constructed on the basis of its mathematical description.

To determine the location and dimensions (geometric parameters) of defects, the barrel-bore radius matrix – considered as an array of coordinates of points on its surface – is first subjected to noise removal and then to clustering of the remaining points. As a result, clusters of points are formed, each corresponding to an individual defect. The subsequent application of vector-calculus methods to these clusters makes it possible to determine the geometric parameters and spatial location of the respective defects.

When applying the considered method to the technical diagnosis of smooth and rifled barrel bores, significant specific features arise due to differences in the mathematical description of the manifestations of diametral wear on cylindrical surfaces and the wear of rifling elements (flanks and lands) of complex geometry.

Taking these features into account, the study presents the list, execution sequence, and detailed content of the operations that ensure the required matrix transformations, defect-type identification, removal of noise points, clustering of significant surface points, and determination of the geometric characteristics (dimensions and location) of each defect. Collectively, these operations constitute the essence of the proposed method for processing measurement data, which offers a comprehensive approach to automated processing of measurement information.

The practical value of the developed method is determined by its suitability for algorithmization and software implementation within automated technical-diagnostics systems, which makes it possible to significantly increase the efficiency and speed of their application.

Further research should be directed toward the experimental validation of the proposed method in order to assess its effectiveness when applied to real firearm barrel-bore samples exhibiting various types and degrees of defect manifestation.

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НАУКОВО-МЕТОДИЧНІ ОСНОВИ ОБРОБЛЕННЯ ВИМІРЮВАЛЬНОЇ ІНФОРМАЦІЇ ПРО ГЕОМЕТРИЧНІ ХАРАКТЕРИСТИКИ КАНАЛІВ СТВОЛІВ ВОГНЕПАЛЬНОЇ ЗБРОЇ

Розглянуто особливості технічного діагностування каналів стволів вогнепальної зброї на основі визначення їхніх геометричних характеристик із застосуванням лазерного тріангуляційного засобу вимірювання. Проведено аналіз наукових публікацій, у яких описано зазначений підхід до технічного діагностування каналів стволів. Установлено, що, незважаючи на значну кількість досліджень у цій сфері, питання оброблення вимірювальної інформації про геометричні характеристики каналів стволів залишається недостатньо вивченим. У зв'язку із цим мета статті полягає в розробленні й обґрунтуванні методу оброблення вимірювальної інформації про геометричні характеристики каналів стволів вогнепальної зброї.

Запропонований у статті метод передбачає оброблення вимірювальної інформації про геометричні характеристики каналів стволів, поданої у вигляді матриць радіусів, і забезпечує автоматизоване визначення виду, розмірів та просторового розташування дефектів на розгортці поверхні каналу ствола. Зокрема, метод містить такі операції оброблення сканованої (досліджуваної) поверхні, поданої матрицею радіусів: порівняння з еталонною поверхнею каналу ствола; видалення шумових точок; виділення дефектів шляхом кластеризації точок; визначення геометричних параметрів дефектів із використанням методів векторного числення; ідентифікацію виду дефекту, яка здійснюється шляхом застосування критеріїв до показника, що характеризує ступінь розбіжності між геометричними характеристиками ділянки каналу ствола з реальним дефектом і *відповідними характеристиками моделі дефекту певного виду, побудованої на основі його математичної моделі.*

Реалізація методу під час технічного діагностування гладких і нарізних каналів стволів ураховує особливості прояву та форми дефектів, притаманних кожному із цих типів каналів стволів.

Практична цінність запропонованого методу полягає у його алгоритмізованості та придатності до інтеграції в автоматизовані системи технічного діагностування, що забезпечує визначення виду, розмірів і просторового розташування дефектів на поверхні розгортки каналу ствола.

Ключові слова: *канал ствола, технічне діагностування, технічний стан, дефект каналу ствола, геометричні характеристики, метод оброблення інформації.*

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