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IMPLEMENTATION OF REENGINEERING TECHNOLOGY TO ENSURE THE PREDEFINED GEOMETRIC ACCURACY OF A LIGHT AIRCRAFT KEEL

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The subject of this research is the technology of reengineering and control of parts of aircraft objects (AOs) and technological equipment for their manufacture. The predefined accuracy of the keel of a light aircraft and molding surfaces of technological equipment for its manufacture has been ensured by using reengineering technology and CAD systems. A portrait of the actual physically existing keel of a light aircraft was built in the *.stl file format using the software Artec Studio (USA). The control and comparison of the geometry of the shapes of the analytical standard with the actual physically existing keel of a light aircraft based on its portrait have been implemented. The methods used are the analysis and synthesis of the experimental geometry of shapes, the method of expert evaluations. The following results were obtained: based on the analysis and synthesis, the presence of significant errors in the accuracy of the manufacture of the keel for a light aircraft in the range from –5.26 mm to +5.39 mm was detected. It has been shown that the key factor is the keel's relative plane indicator, which is outside the tolerance margin and is 85 %. It was decided to fabricate new technological equipment from another material – organic plastics. Control of the technological equipment made from organic plastics for the keel of a light aircraft showed that the shape-forming surfaces of the equipment have appropriate shapes and sizes corresponding to the existing analytical standard and are devoid of inaccuracies that occurred in the previous version. The range of keel margins that was made using the new technological equipment from organic plastics is from –0.51 mm to +0.34 mm while the relative plane of the keel outside the tolerance margin does not exceed 15 %. The study results showed the adequacy of the decisions taken, ensuring the predefined accuracy for the keel of a light aircraft and molding surfaces of technological equipment for its manufacture

Keywords: reengineering of aircraft objects, analytical standard, accuracy of shapes and sizes, technological equipment

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1. Introduction

The aerospace industry is characterized by large dimensions of articles and technological rigging, the dimensions of which can reach tens of meters. At the same time, it is necessary to maintain accuracy of several millimeters. Moreover, in the context of the rapid development of modern aircraft construction, the requirements for the characteristics of aircraft objects (AOs) are constantly growing. The reliability and efficiency of AOs depend to a large extent on ensuring the geometrical accuracy of their components (parts and assemblies). That is why coordinate measuring machines (CMM) and systems [1–3] were, and still are, the most relevant and promising in the aerospace industry. They are used in the execution of many operations of machining, assembling, measurements, as well as reengineering and control operations involving the parts and elements for the preparatory, stamping, and assembly equipment, stretching dies, surface standards, etc. [4].

The technology of reengineering based on CMM has become widely used in the repair and restoration of AOs whose parts are worn out and do not meet the specified requirements and standards of flight suitability of the aircraft. It should be borne in mind that the AO geometry is not simple, and, when using template methods, the accumulated deviations in their manufacture are also transferred to AOs, which degrades the accuracy of AO in general. In addition, it should be added that when making changes to the AO geometry, there is a need to make new templates while the previous templates can be safely disposed of. Modern equipment used by reengineering technology makes it possible to reproduce the AO geometry with almost 0.01 mm accuracy, and the presence of an analytical reference in CAD systems eliminates the need for material costs for additional fabrication of template equipment [5]. That also applies to AOs designed in the Soviet time, based on which further modifications are built, for which their digitization becomes relevant [6].

Given the spread of the use of reengineering technologies throughout the life cycle of an article, the research is relevant that aims to implement reengineering in the process of monitoring the accuracy of the manufacture of aviation articles. Accuracy control in line with this technology is implemented on the basis of a three-dimensional model according to the analytical standard as the primary source of reference.

2. Literature review and problem statement

Reengineering in modern production is a complex procedure that involves making radical changes to manufacturing processes in order to minimize the use of production resources, reduce the duration and cost of the production cycle, improve article quality [7]. Thus, work [8] shows the algorithm for predicting the cost of building a complex project and technological ways to accelerate the time at the stages of modeling, which can only be useful at the stage of 3D modeling of reengineering. In [9], the concept of "reengineering" is presented as proper recommendations for changing the parameters of the technological process in order to further construct a new or improved object production; however, this does not give a complete picture in accordance with the definitions in [7]. The authors of [10] attempt to explain the process of reengineering involving neural networks and give a model for the use of this technique industrially; however, that is not confirmed by practical introduction and implementation. Work [11] reports the results of reengineering for 3D modeling of the turboprop rotor blade and shows that importing and exporting files in CAD systems sometimes results in loss of geometric information. Study [12] gives a model of an expert system in the reengineering of technological equipment in the processing industry using artificial intelligence, decision-support systems, etc.; however, the implementation of that model at the start is very expensive. AO reengineering can most often be found at the stages of control and measurement as part of automated or robotic AO assembly systems [13]. Despite the practical significance of such results, AO reengineering as an engineering method for studying AOs has not been considered in detail. Accurate information on the geometry, structure, design, and functioning of AOs would make it possible to obtain spatial information for its further duplication or improvement, which, in turn, could provide for a high level of scientific and technological progress. This approach is reported in [14], which describes spatial information as a digital layout in a unified design environment that includes a set of electronic documents for a particular component. However, the positioning of AOs in the space for assembly units is not considered. The solution is given in [15], which reports the recognition methods and the algorithm for positioning an experimental AO in space. However, the verification of the proposed approach is not shown; no ways to associate it with the means of technological equipment are considered. An option to address this issue may be to use prototyping technology according to the recommendations given in [16]. In turn, the digital layout is built according to the analytical standard of the geometry and shape of an article, which is constructed according to the axioms of metric geometry of Euclid or Gilbert or Birkhoff [17]. Once there is an analytical standard for the examined object, it simplifies control based on reengineering technologies by scanning an actual existing research object and comparing the resulting portrait with the analytical reference. With this technology, it is only possible to obtain results related to the geometry and shape of the examined object; it is not clear whether they would suffice for conclusions on the adequacy of control. This fact gives grounds to assert that it is advisable to conduct research into this area.

3. The aim and objectives of the study

The purpose of this study is to ensure the specified geometrical accuracy for the keel of a light aircraft and the molding surfaces of technological equipment for its manufacture using reengineering technology and CAD systems. This could guarantee the reliability and efficiency of light aircraft in general.

To accomplish the aim, the following tasks have been set:

– to construct a portrait of the actual physically existing keel of a light aircraft in the *.stl file format using the software Artec Studio, and convert it into a 3D *.cdw model while preserving geometry and shape;

– to implement control and compare the geometry of the shape of the analytical standard with the actual physically existing keel of a light aircraft according to its portrait;

– to devise recommendations for ensuring the specified accuracy of the keel of a light aircraft.

4. The study materials and methods

Our study is based on the general provisions from the technology for producing aircraft and the general provisions of the theory of machines and mechanisms. During the research, general scientific and special methods of research on analysis and synthesis were used – for preliminary analysis with the statement of the problem, determining research areas, defining assumptions related to the search area.

The term "3D model" is a connected solid that possesses a predefined set of properties and is obtained as a result of the operation within a technological process. The main features of this model are the presence of three types of characteristics:

1) geometry – one or more surface equations:

$$F_A\left(X_{GP}, Y_{GP}, Z_{GP}\right) = 0, \tag{1}$$

in the coordinate system (0, X, Y, Z), which is firmly connected with the solid body (X_{GP}, Y_{GP}, Z_{GP} are the coordinates of the boundary points of the part);

2) a set of surface material (physicochemical) parameters depending on the measurement point at the surface of the part:

$$\alpha_{iP} = \alpha_{iP}\left(X_{GP}, Y_{GP}, Z_{GP}\right), \tag{2}$$

where i is the conditional number of the surface parameter, for example, hardness;

3) a group of three-dimensional material parameters, for example, β_{jP}, measured in the regions that lie inside the part:

$$\beta_{jP} = \beta_{jP}\left(X_{GP}, Y_{GP}, Z_{GP}\right), \quad (3)$$

where *j* is the volumetric parameter number, for example, the local plane, the elasticity module, the composition of chemical elements, etc.

To accomplish the goal and solve the tasks related to the goal, it would suffice to confine ourselves to the first two attributes.

The "the surface of a part" term refers to the surface that limits the part and separates it from the environment – the actual surface [18, 19]. This surface is formed in the process of its manufacture and differs from the rated (reference) surface. By the error of manufacture, its accuracy is understood as the deviation of the obtained in the manufacture of the value of geometric or another parameter from the specified (reference) [20]. Absolute error is expressed in the units of the parameter under consideration. Macro geometric deviations are considered in large areas of the actual surface of parts and characterize the accuracy of the part (cone-shaped, ovality, etc.):

$$\Delta X = X_A - X_N, \quad (4)$$

where X_A and X_N are the actual and rated value of the parameter, respectively.

When asymmetrically positioned, the value of the parameter is set to its mean. The ratio of absolute error to the predefined value of the parameter is termed the relative error $\Delta X/X_N$ or $\Delta X/X_N \times 100$ %.

The "deviation in the shape of a predefined profile" term is based on definitions from [18, 19] as the greatest deviation of actual profile points from the corresponding points of the rated profile, determined by the normal within the normalized region. Measuring the deviation of the normal to the rated profile requires the presence of a measuring device that can perform this type of measurement. However, it is necessary to choose exactly that CMM, which can carry out measurements, for example, of complex profile surfaces by moving the measuring tool according to the normal to the rated surface at each point of the actual part.

5. Results of research on ensuring the specified geometrical accuracy of the keel of a light aircraft

5. 1. Building a portrait of an actual physically existing keel of a light aircraft

As an experimental AO, we chose the keel of a light aircraft made of composite materials (Fig. 1); the CMM employed was a three-dimensional portable scanner, the Eva Lite model, manufactured by Artec (USA). The selected scanner works according to the method of structured white light and provides high accuracy of the surface of the scanned object – a portrait [21].

Portrait dimension data typically do not contain topological information and are, therefore, converted into files of grid structures with a triangular element shape (STL). The next step is to export the *.stl file and model it in any available form: a set of surfaces of heterogeneous rational NURBS splines or a solid-state model in CAD systems (SolidWorks, CATIA, Geomagic Design X, etc.) (USA) [22]. The measuring accuracy, the minimum object size for scanning, portability, and ability to operate basic formats have become determining factors in choosing keel scanning equipment (Table 1).

Fig. 1. The keel of a light aircraft

The software for 3D scanning and processing of data acquired during the research was Artec Studio. With the help of Artec Studio, several keel surface grids were obtained in the form of scans, which were then combined into a single grid by the software internal algorithms – a portrait in STL format for further work with it. The choice of Artec Studio is justified by full compatibility with the selected scanner made by the same developer, as well as the high-quality optimization with modern computers and the availability of full functionality for scanning.

Fig. 2 shows the stages of scanning the keel and building its portrait in the form of a model of a polygonal grid.

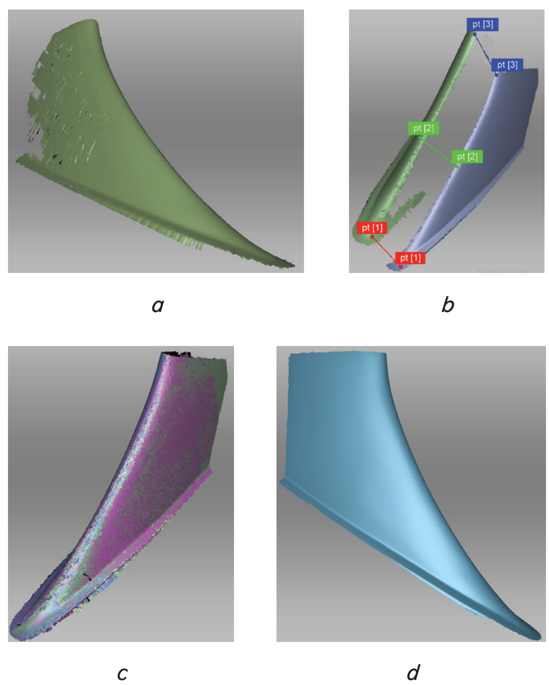
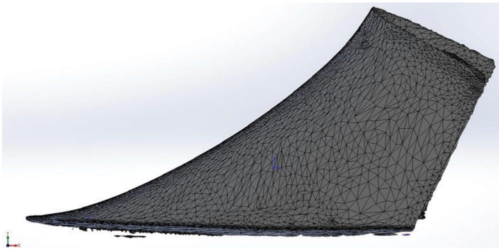


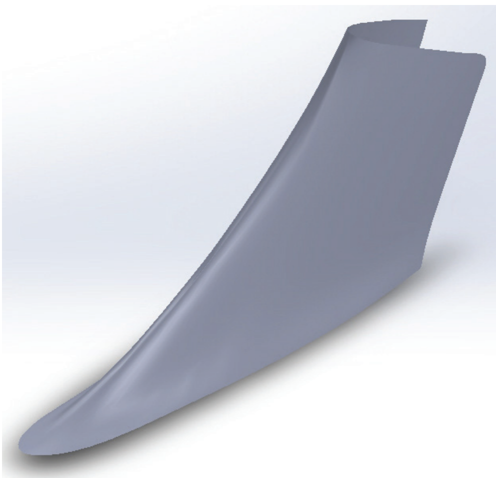
Fig. 2. Stages of building a portrait of the keel of a light aircraft: *a* – scan acquisition; *b* – a combination of the resulting scans; *c* – primary processing of scans; *d* – building a portrait of the keel

To construct a 3D model from the *.stl file, the SolidWorks software package was selected owing to its ScanTo3D editing tools and the capabilities of converting such files into a solid-state model (Fig. 3).

It should be noted that the portrait of a keel implies precisely its analytical portrait as a mathematical model in terms of analytic geometry, which possesses data on the shape and size of a keel in the CAD system. Proving the keel identity to the analytical standard involves correlating the analytical portrait with the analytical standard.



a



b

Fig. 3. Constructing a 3D model of the light aircraft keel in SolidWorks: *a* – a polygonal grid of the *.stl file; *b* – the *.stl file converted to the *.cdw file

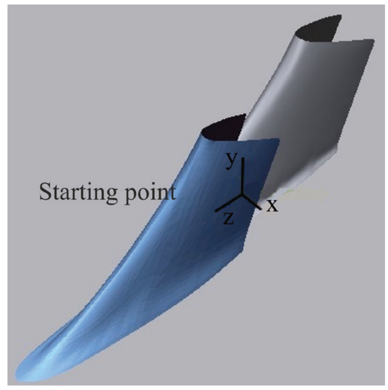
Table 1

Basic characteristics of the scanner Eva

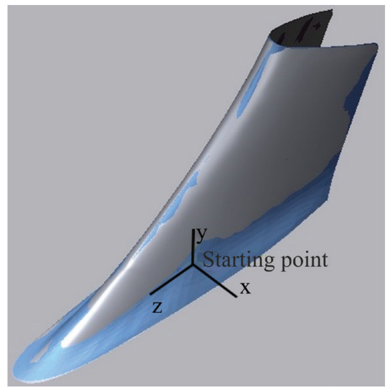
Parameter	Value
Measurement accuracy	0.1 mm
resolution	0.5 mm
The minimum size of the object to be scanned	100 mm
Keeping the trajectory without markers	based on shape
Read speed	16 frame/s
Output formats	STL, OBJ, PLY, BTX, etc.
Scanner weight	0.9 kg

5. 2. Implementing the control and comparing the geometry of analytic reference shapes with a portrait of the light aircraft keel

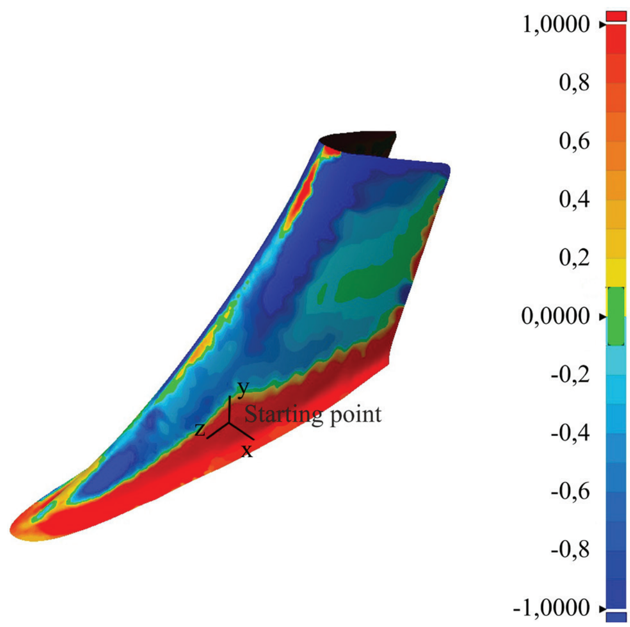
Geomagic Control X (USA) software was used to control the accuracy of the keel of a light aircraft (Fig. 4). In order to import data into the programming environment, the solid-state 3D model was converted to the *.stl format. It should be clarified that converting a 3D model into a polygonal grid is not a return to the same form as it was before processing in the SolidWorks package. In fact, the keel is divided into simpler elements while maintaining geometry, unlike the scan-based grid. The analytic keel reference is in the X_T format (Parasolid geometric modeling kernel format).



a



b



c

Fig. 4. Stages of keel accuracy control: *a* – primary position of the model relative to the standard; *b* – combining a 3D model and an analytical standard; *c* – a visual display of control results

During the analysis of data given in the generated report from the Geomagic Control X software, the presence of significant errors in the accuracy of the manufacture of the keel of a light aircraft was confirmed. That is, the maximum positive error is +5.39 mm, while the negative error is –5.26 mm. At the same time, average values are not so critical: +0.94 mm and –0.65 mm for the positive and negative error, respectively. However, a more significant role belongs to the relative plane of the keel occupied by the surface outside the tolerance field: this indicator is 85 %. In other words, almost the entire keel has large deviations from the analytical standard based on which it is made.

5. 3. Devising recommendations to ensure the specified geometrical accuracy of the keel of a light aircraft

Taking into consideration our results of keel control, where the range of errors is from −5.26 mm to +5.39 mm, a proposal was made to control the technological equipment at which the keel was manufactured. This is necessary to establish the causes of the keel defects: whether it is the technology of its manufacture or the inaccuracy in the forming surfaces of the technological equipment. The results of control of the technological equipment with the help of scanning showed the identity with the results of control obtained from the keel, so it was decided to fabricate new technological equipment. The new technological equipment is made not of fiberglass, which is widely used for such AOs, but from organic plastics. The main criterion for choosing organic plastics was their greater strength and smaller weight compared to fiberglass, as well as no need for post-wetting. The new technological equipment consists of a matrix and a component of a punch where their shape-forming surfaces were built on the basis of the existing analytical keel reference (Fig. 5).

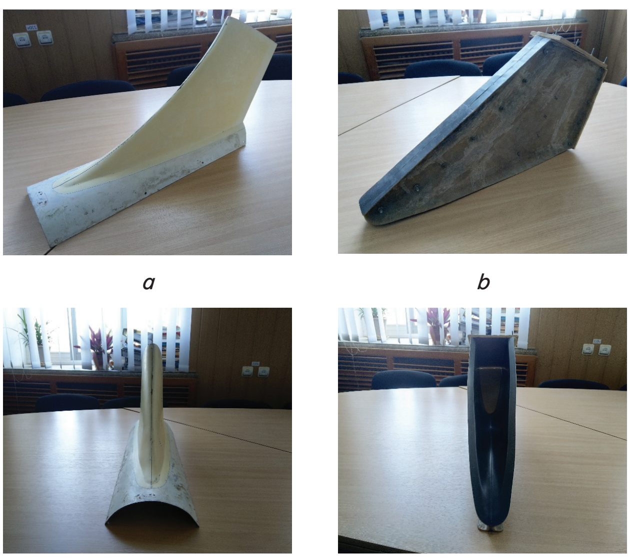


Fig. 5. Technological equipment for the manufacture of keel: *a* — matrix (isometry); *b* — punch (isometry); *c* — matrix (shape-forming surface); *d* — punch (shape-forming surface)

After measuring the means of technological equipment made from organic plastics, it was found that the shape-forming surfaces of the technological equipment made of organic plastics take the shapes and sizes corresponding to the analytical standard and are devoid of inaccuracies of the previous version. The range of deviations from the analytical keel reference, made at the technological equipment from organic plastics, is from −0.51 mm to +0.34 mm, while the relative plane of the keel outside the tolerance field does not exceed 15 %. At the same time, according to industry regulatory and technical documents, the boundary deviations of the keel contour from the analytic reference are ±2 mm, that is, the deviation of the actual keel contour from the analytical reference does not exceed the limits. This confirms the expediency of the decision on the manufacture of technological equipment from a new material – organic plastics.

6. Discussion of results of studying the accuracy of the geometry and shape of a keel

The portrait built from an actual physically existing keel of a light aircraft in the *.stl format taking into consideration the accuracy provided by the selected EVA Lite scanner (Table 1) made it possible to reach the geometry and shape of the keel with an accuracy of ±0.1 mm.

Control is implemented after the stages of transformation of the portrait from *.stl to a 3D model in the SolidWorks software, and back to *.stl in the Geomagic Control X package, followed by its comparison with the *.x_т analytical reference of the keel. Exporting the files based on *.stl in CAD systems made it possible to preserve the geometry and shape while the results of control were considered reliable and adequate compared to the data reported in [11].

Unlike contact control methods, where the result of measurements depends on the level of professionalism of the controller, a contactless method based on scanning does not require special knowledge from the controller. In addition, there are no following disadvantages in the contactless control method:

– duration and time-consuming measurement process;

– the impossibility of re-adjustment contact devices or replacement of templates in accordance with changes in the geometry and shape of an article.

It should be noted that AO reengineering can most often be found at the stages of control and measurement as part of automated or robotic AO assembly systems; however, in this study, such systems are not necessary. On the contrary, their absence makes it cheaper and simplifies the reengineering technology described in papers [12, 13].

The results of the introduction of reengineering technology to ensure the predefined geometrical accuracy of the keel of a light aircraft was the manufacture of new means of technological equipment (matrix and punch) from another material (organic plastics). The main basic information in the control operations of such technologies is the presence of data on the analytic geometry – the surface reference, which:

– combines spatial information as a digital mock keel proposed in work [14];

– verifies the approach set out in [15] as a totality of spatial information (geometry, structure, design, and functioning) about the examined keel with technological equipment tools.

A special feature of the proposed method is the possibility of updating the analytical standard according to the actual physically existing prototype. Solving this task involves restoring the reference according to the scanned information about the portrait where prototyping technology can also be used according to the recommendations from [16]. However, if we compare the amount of information about the analytical benchmark of the prototype and its portrait, the latter contains information exclusively for the implementation of control operations, the volume of which is significantly less than is contained in the corresponding analytical standard. It is also necessary to take into consideration the complexity and limitations in the construction of the analytical standard, which is proven in work [17] where the reference is built according to the axioms of the metric geometry of Euclid or Gilbert or Birkhoff. The creation of a model of the prototype must be carried out according to the measurements of the coordinates of points at the surface of the prototype in the same coordinate system as the future analytical reference. For these reasons, the construction of an analytical standard of the keel according to portrait data should be carried out taking into consideration its would-be manufacture technique, aerodynamics data, strength, errors in the method of referencing, etc. Actually, the complexity of building an analytical standard is its drawback. It is possible to facilitate the task only by using the latest CAD systems based on analytic geometry according to the theories of spline functions, which should be primarily justified in production. A spline, in this case, connects the surface points of the prototype and forms analytic geometry, and affects its accuracy. Therefore, ensuring the predefined accuracy for the geometry and shapes based on reengineering technologies is impossible without the use of in-depth theories of spline functions, CAD systems, software based on them, as well as modern technical solutions in production.

7. Conclusions

1. The proposed reengineering technology for a keel of a light aircraft based on the selected modern CMM (Eva Lite scanner of Artec, USA) makes it possible to obtain adequate results with an accuracy of up to 0.1 mm. The main factor in the choice of the scanner Eva Lite, in this case, is its characteristics to ensure sufficient accuracy for the keel of a light aircraft, where the limit deviations of the layout from the theoretical one are ±2 mm. It is shown that the geometry and shape are assured based on a single *.stl file format for different software packages of a CAD system.

2. A key factor for the implementation of control over the keel of a light aircraft and technological equipment tools is the proper construction of their portraits in a CAD system. The analysis of the data given in the generated report from the Geomagic Control X software revealed the presence of significant errors in the accuracy of the manufacture of the keel of a light aircraft and existing means of technological equipment. These errors were in the range of 5.26 mm to +5.39 mm, while the relative plane of the keel outside the tolerance field was 85 %. Such results allowed us to assert that both the keel and technological equipment can be rejected.

3. The proposed solution for the manufacture of new means of technological equipment from organic plastics showed that the shape-forming surfaces of technological equipment made of organic plastics take shapes and sizes corresponding to the analytical standard and are devoid of inaccuracies of the previous version. The range of deviations from the analytical keel reference, made at the technological equipment of organic plastics, is from –0.51 mm to +0.34 mm, while the relative plane of the keel outside the tolerance field does not exceed 15 %. This becomes possible precisely by ensuring the specified geometry and shape of shape-forming surfaces.

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