The object of this paper is the geometric accuracy of the acquired portrait from the 3D printed full-scale sample in the reduced size of the convex-concave parts compared to the correspondingly reduced ideal one.

The subject of research is reverse engineering and additive technology for manufacturing convex-concave parts for mechanical engineering (ME). A new prototyping methodology for convex-concave parts of mechanical engineering objects has proposed. Underlying the methodology is the use of the scaled (by reducing in size) ideal portrait of the 3D scanned original part. The decision to start the production is made by comparing the geometry of the portrait acquired from the 3D printed sample in reduced size with the ideal one, provided that the values are within the tolerance range. The following results were obtained. A design and technological analysis of the blade of the pumped hydroelectric power station was performed, after which a 3D scanner and a 3D printer were selected. A 3D scan of the blade with the formation of a portrait in the STL format file was implemented, as well as its refinement into an ideal one. From the geometric features and shapes of the blade, as well as the technical characteristics of the 3D printer, the percentage of reducing the sample for printing (by 75 % of the original dimensions) was calculated. According to the rated dimensions of the original part and the reduced sample, the tolerance field was set for the size: 0.6 mm and 0.25 mm, respectively, at 12 quality of the part's manufacturing accuracy. Inspection of the printed sample and comparison with the correspondingly reduced ideal portrait revealed a deviation from –0.123 to +0.120 mm, which is within the defined tolerance field for the manufactured reduced sample. The results of experimental studies confirmed the adequacy of the proposed methodology for prototyping the mechanical engineering parts and verified the theoretical foundations of reverse engineering for convex-concave parts of any large size by using a proportional reduction in the size of finished portraits

Keywords: reverse engineering, methodology, parts, digital layout, 3D scanning, 3D printing, geometric accuracy

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DEVISING A METHODOLOGY FOR PROTOTYPING CONVEX-CONCAVE PARTS USING REVERSE-ENGINEERING TECHNOLOGY PROVIDING THE PREDEFINED GEOMETRIC ACCURACY OF THEIR MANUFACTURING

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1. Introduction

Modern aviation production is in search for optimal strategies in order to improve product quality and optimize technological processes. One of these ways is the use of reverse engineering, which allows to digitize existing samples of mechanical engineering objects (MEOs) if there is no documentation for them, perform post-operational control during the manufacture of such MEOs, create prototypes, etc. [1]. The technology of reverse engineering involves scanning the research object, finalizing the surfaces acquired by scanning and building a digital mock-up (DMU) or comparing to it during inspection operations [2]. Reverse engineering solves two of the most important production problems. The first is a direct task when a DMU is first designed, which is used for post-operational inspection and manufacturing of a MEO part. The second is the inverse problem when a DMU is designed based on an existing real physical object – a MEO part [3]. However, the main peculiarity of the reverse engineering technology is the ability to obtain quickly measurement results and inspection with high accuracy from 0.1 to 0.05 mm [4]. This is especially relevant during prototyping, repair, and modernization of the MEO structure, control over the installation of new equipment on board, etc. Therefore, the integration of reverse engineering into the process of DMU designing and quality inspection of MEO allows to monitor constantly the production process and respond promptly to any deviations, providing for the stability and reliability of produced items in the shortest possible time compared to conventional technologies. In this context, the development of reverse engineering technologies becomes not only a way to improve quality but also a key factor in ensuring competitiveness in the market of production services.

However, the disadvantages of reverse engineering technology should also be noted. Firstly, it is expensive equipment and scanning devices, as well as the complexity of implementing the technical preparation of production in already existing production chains, which deters manufacturers from their purchase and implementation. Secondly, it is the need to train highly qualified specialists in 3D scanning and 3D modeling. The latter is key factor when processing the acquired scanned surfaces – a portrait in the STL format and its subsequent transformation into a high-precision DMU with minimal time costs. This especially applies to complex profile parts and structures for pumping nuclear and hydroelectric power plants, boiler houses, and furnaces of various capacities [5, 6].

Research on the prototyping of MEO parts is determined by its wide demand for use in the production of parts and repair of various structures. A significant role in ensuring the geometric accuracy of the manufactured part in such a case belongs to the high-experienced scanning operator as well as the DMU construction technology. It should be noted that the information volume of DMU is quite large and requires powerful computer equipment and software. Therefore, manufacturers of MEO parts design digital twins on the basis of existing DMU, attaching specific functions or technological processes to it [7, 8]. However, the desire of manufacturers to reduce the labor-input and time of technical preparation of production led to a reduction in the number of stages in the technological chain by refining the acquired portrait. Therefore, recently there has been a tendency to process the acquired portrait in the STL format with high accuracy and use it to manufacture the part using additive or extractive technologies [9]. The only problem is the verification and confirmation of the adequacy of the finished portrait, which predetermines the relevance of our research.

2. Literature review and problem statement

A significant role in ensuring the geometric accuracy of DMU belongs to the high qualification of the scan operator and the use of appropriate 3D scanning equipment. For example, work [10] reports a comparison of the measurements of the parts obtained during the cutting process, when using the coordinate-measuring machine (CMM) and three optical scanners. It is noted that CMMs still hold their position in terms of the scanning accuracy, therefore the received portraits accuracy, but there are also positive forecasts for 3D scanners, considering that accuracy is increased, and appropriate software is developed. A continuation of the studies reported in [10] is the results given in [11], in which a robotic arm, a 3D scanner, and a rotary table, on which a simple industrial part is located, are combined into a system. The authors suggest to add to the software the calibration of the «scanner camera – rotation of the object on the table» system, which makes it possible to reproduce a virtual 3D scan with increased accuracy. The experimental results have demonstrated high accuracy and better performance in system calibration, scan path calculation, and multi-angle scan data fusion on mechanical engineering parts of simple shapes. However, for complex-profiled, convex-concave parts, such approaches could be time-consuming and difficult to perform as they require step-by-step inspection in the corresponding cross-sections. As shown in [12], even when using the same software with wide functionality, the characteristics of the selected 3D scanner are essential in scanning, not only in terms of scanning accuracy, but also in terms of resolution. By correct selecting the scanner, location and number of markers on the surface of the test part, it can be reduced the time for processing the scanned portrait and increased its accuracy. Therefore, studies [10–12] proved that the most important problem is to acquire a portrait with high accuracy, which, in turn, affects the decision of the need to build a DMU, provided that the part is manufactured using either additive or extractive technologies. Thus, work [13] demonstrates the sufficiency of the geometric accuracy of the portrait in the STL format, which meets the requirements of the total allowable error for the manufactured part using additive technologies. Despite the positivity of the results, which was confirmed when inspection the part manufactured by 3D printing, the use of the presented methodology, which is called sustainable reverse engineering, raises doubts about ensuring the geometric accuracy of complex shaped and convex-concave parts. Thus, the authors of paper [14] concluded that the existing software capabilities for correcting a portrait to an ideal one not always meet the requirements for geometric accuracy up to ±0.5 mm for the manufacture of a complex profile part by 3D printing. In this case, the portrait of the part, which has surfaces with a fillet radius of up to 0.5 mm, sharp corners, threads, etc., can become only the basic geometry for the construction of a DMU of the specified dimensions. An alternative is work [15], which presents the PHENIX methodology, which makes it possible to perform 3D modeling of the DMU based on the acquired portrait of convex-concave parts (profiled pipes and blades of double curvature). It is found out that the results obtained from the reconstruction of the DMU using PHENIX are considered positive according to the requirement to ensure the geometric accuracy of the reconstruction of the DMU from 0.8 to 1.2 mm for profiled pipes and 1.0 mm for the blade of double curvature. However, the authors of [15] did not take into account the fact that an error occurs during the manufacture of the part, and it is the final total error that should be taken into account to make a decision about the results positivity. It should also be noted that rebuilding the DMU is quite time-consuming and compared to the requirements of geometric accuracy of ±0.5 mm in work [14], such results cannot be positive for implementing into production. Therefore, the use of PHENIX is possible only for prototyping and modernization, provided that the DMU is adjusted for geometric accuracy, but not for inspection operations. A series of studies [2, 16] show the importance of acquiring and finalizing a portrait with high accuracy into an ideal one, as well as the importance of the method chosen for approximation and processing of the surfaces acquired by 3D scanning. For example, [2] analyzed the capabilities of software for processing flat surfaces and intersecting surfaces with filleted corners. In work [16], an approach to finalize the point cloud (portrait in the STL format) is proposed, which, in turn, removes the need for additional scanning operations. The only drawback is their automatic post-processing, which reduces the accuracy of geometric dimensions. Work [17] demonstrates three options for obtaining surfaces (photogrammetry, 3D scanning, and 3D modeling), where the final result is a comparative analysis of the total time and quality of manufacturing prototyped parts using additive technologies. The authors concluded in favor of 3D scanning but did not report data on the resulting geometric accuracy. Work [18] shows the full cycle of prototyping a part using reverse engineering and additive technologies. However, in this case, it comes about designing a DMU from the acquired portrait of the part and using it to manufacture the part by 3D printing. Inspection of the obtained part geometry was also provided according to the DMU data. Therefore, it's the best to access the adequacy of engineering decisions taken during the portrait processing and the reconstruction of the reverse-engineered DMU by the part manufactured according to them. It should be noted that for large-sized convex-concave parts (MEO panels, blades of nuclear and hydroelectric power plants, etc.), full-scale experiments are always expensive and require technicians of high qualification. Therefore, there is a need to devise a methodology for prototyping such MEO parts providing for the specified geometric accuracy under conditions of limited time and funds.

3. The purpose and objectives of the study

The purpose of the research is to devise a methodology for prototyping convex-concave parts of MEOs, ensuring the specified geometric accuracy of the manufactured parts. This will allow to implement engineering solutions quickly in reverse engineering for the refinement and reconstruction of both the acquired portraits and DMUs, as well as for increasing the accuracy of the production of a full-scaled part.

To achieve the purpose, the following scientific tasks have been defined:

– to design a portrait file in STL format of a blade for a pumped hydroelectric power plant;

– to finalize the acquired in the STL format portrait of the blade for the pumped hydroelectric power station into an ideal one;

– to inspect the geometry of the designed portrait from the 3D-printed full-scale sample in reduced size according to the correspondingly reduced ideal portrait of the blade for the pumped hydroelectric power plant.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of the study is the geometric accuracy of the acquired portrait from the 3D printed full-scale sample in the reduced size of the convex-concave parts of MEO in comparison with the correspondingly reduced ideal one.

The hypothesis of the research assumes that inspection of the geometric accuracy of the refined, i.e. ideal portrait can be provided using the acquired portrait of the experimental part, which was printed using additive technologies. At the same time, for large-sized parts, such verification is possible using an ideal portrait of the reduced size, provided that the tolerance on the rated size of the printed sample is determined. That is, in the absence of technical specification on the tolerances of form, orientation, location and run-out, these deviations are limited by the size tolerance field from reference data generally accepted in mechanical engineering [19].

The research is based on the general principles of the production technology of the aerospace technology (AT) [20]. During the work performing, the methods of general scientific and empirical research on analysis and synthesis were applied – for the preliminary statement of the problem, determination of the direction and assumptions regarding the research area, as well as field experiments and inspection.

The research was carried out in the following steps:

1 – design and technological analysis of the experimental sample;

2 – selection of the required scanning device;

3 – 3D scanning;

4 – processing of the acquired scanned surfaces and creation of a portrait – a STL file;

5 – creating the ideal portrait from the geometry of the acquired portrait data;

6 – 3D printing of a full-scale sample in a reduced size based on the data of an ideal portrait of the STL file, which is accordingly reduced;

7 – inspection, that is measuring and comparison of a portrait acquired from a life-size sample in reduced size with a correspondingly reduced ideal portrait;

8 – analysis of the results and making conclusions.

4. 2. The study subject

The subject of the study is the formation of geometric accuracy of convex-concave parts for AT using the technologies of reverse engineering and 3D printing. A blade for a pumped hydroelectric power station was chosen for experiments as the test part. According to the design and technological analysis, the ARTEC Leo (Luxembourg) 3D scanner (Fig. 1) with the characteristics listed in Table 1 was selected [21]. Such a scanner has a scanning accuracy of 0.1 mm and a resolution of up to 0.2 mm, which satisfies the field of tolerances for the dimensions of the MEO test part [19].

Fig. 1. 3D-scanner ARTEC Leo (Luxembourg)

Table 1

Specifications of the 3D scanner ARTEC Leo (Luxembourg)

Parameter name	Parameter value
Display	Built-in touch panel screen
Processing	On-board real time processing
Volume capture zone	160,000 cm^3
3D reconstruction rate, up to	80 FPS
3D resolution, up to	0.2 mm
3D point accuracy, up to	0.1 mm
Color resolution	2.3 mp
Structured-light source	VCSEL
Position sensors	Built-in 9 DoF inertial system
Multi-core processing	NVIDIA Jetson TX2
Power source	In-built exchangeable battery
Connectivity	Wireless

Fig. 2 shows an experimental part – the blade for a pumped hydroelectric power plant.

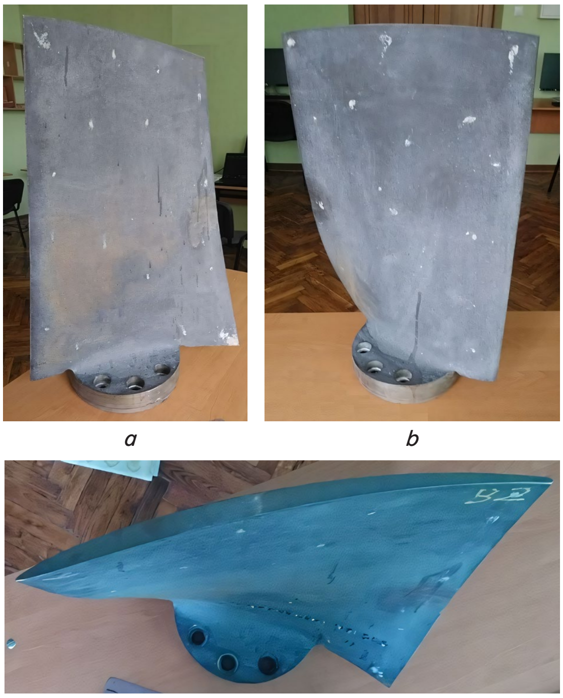


Fig. 2. Pumping hydroelectric power plant blade: *a* – one side; *b* – another side; *c* – top view

For quick and easy construction, as well as for obtaining accurate and mathematically defined models, modeling using simple geometric figures, primitives, was used [22].

3D models are understood as 3D objects that use a set of points in 3D space connected to each other by various geometric objects such as triangles, lines, etc. [23].

The term «digital model» means a model developed by means and tools of CAD systems using spline geometry [24].

A portrait is a set of point data in the form of a data file – point cloud acquired as a result of surface 3D-scanning [25]. A point cloud is a set of vertices in a three-dimensional coordinate system defined by the *X*, *Y*, and *Z* coordinates.

3D printing of a full-scale sample in the reduced size of the experimental part, a blade for a pumped hydroelectric power plant, was performed on a 3D printer CREATBOT F430 (CHINA) [26].

The «deviation of the shape of the given profile» according to the definitions given in [27] was accepted as the parameters of inspection and comparison of the acquired portraits. The geometric dimensions of such deviations are the largest deviation of the points of the real profile from the corresponding points of the rated profile, which is determined by the normal within the normalized area.

The portrait measurement data did not have topological information and therefore were converted into files of grid structures with triangular elements (stereolithography – STL format file) [28, 29].

Design of an ideal portrait involved finalizing the acquired portrait of the scanned blade for the pumped hydroelectric power station using software Geomagic Design X (USA) [30].

Inspection of deviations in the portrait acquired from the printed full-scale sample was performed by comparing it with the ideal one.

5. Results of research on the part manufacture under time-limited conditions

5. 1. Designing a portrait of a blade for a pumped hydroelectric power plant with determining the time for its construction

The structural and technological analysis revealed that the blade has the shape shown in Fig. 3:

– convex-concave shape with variable profile, i.e. double curvature;

– variable wall thickness (the largest thickness in the cross-section ranged from 17.964 to 32.546 mm) along the height (640.46 mm);

– through holes with variable diameters (from 21 to 34 mm) of cylindrical shape;

– there are 90° angles and fillet radii in holes (up to 4 mm);

– the height of the blade shank is 52.11 mm;

– the inter-center distance of the holes is 188 mm.

In order to obtain a closed scanned surface of the blade for the pumped hydroelectric power plant, it was performed the scanning first on the one side, then the other one, and finally – the joining shank. Fig. 3 shows a portrait of the blade for a pumped hydroelectric power plant.

Plasticine markers were used to simplify the assembly of the acquired scans, which facilitated the design of a single polygonal grid in the ARTEC Studio program, which is the software for the ARTEC Leo scanner. Owing to them, the comparison of the scanned surfaces was performed according to the obtained geometry and a real portrait of the blade for the STL file was created. Difficulties with scanning were detected only for holes and edges, the surfaces of which were refined at the next stage – when designing an ideal portrait.

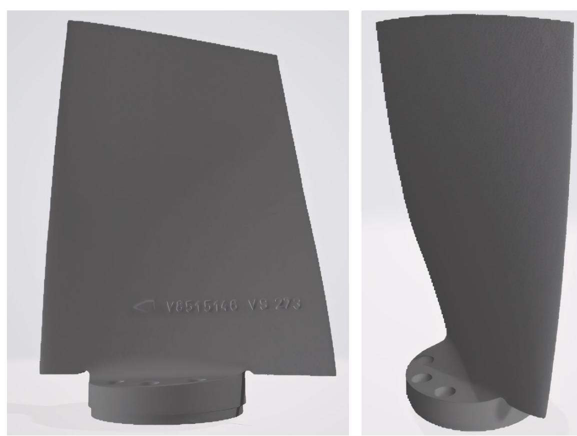


Fig. 3. Portrait of a blade in STL format: *a* – view from one side; *b* – view from the other side

5. 2. Designing an ideal portrait of a blade for a pumped hydroelectric power plant with determining the time for its construction

Fig. 4 shows an ideal portrait of the blade after processing the acquired portrait (Fig. 3) in the Geomagic Design X software. It should be noted that the markings and markers of the blade on the model were removed by appropriate software tools.

There were used the following tools that have proven efficiency according to the results reported in [14]:

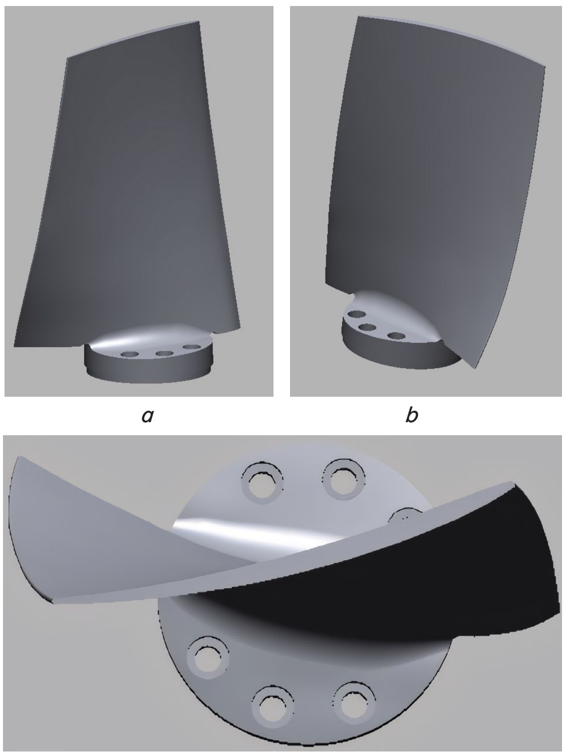
1. «Healind Wizard», which detected and fixed self-intersections, spikes, small components, tunnels and holes of the polygon model.

2. «Decimate», which reduced to the desired number or percentage of polygons in a polygon mesh without degrading its detailing.

3. «Optimize Mash», which allow to obtain more uniform triangles by optimizing the mesh.

4. «Defeature», which removed and restored the highlighted area using intellectual algorithms. This tool was used to remove from surfaces the unnecessary holes, some defects, and markers that were applied for tracking during scanning.

5. «Fill Holes» allows to fill unnecessary chips and holes, as well as align their edges. This function is useful when there is a need to fill «complicated» surfaces or unnecessary discontinuities and holes, etc.



a *b*

c

Fig. 4. An ideal portrait of a blade for a pumped hydroelectric power plant: *a* — a view from one side, *b* — a view from the other side; *c* — a view from top

5. 3. Inspection of the designed portrait geometry using the 3D-printed sample with a reduced size based on the ideal portrait of the blade

Verification and inspection of the geometry of the ideal portrait in the STL format in order to make a decision on the possibility of using it for the production of a blade using additive or extractive technologies involved the following. It was decided to implement 3D printing of the blade sample in reduced size based on the ideal portrait file. The reduction is necessary in order to minimize the use of material for test samples when selecting printing modes, laying layers of plastic when providing angles and fillets, etc. The percentage of reduction of the blade sample for printing was taken based on:

– 3D printer working area;

– the diameter of the nozzle or the diameter of the original molten plastic (0.2 mm);

– minimizing the use of material and printing time (up to 8 working hours);

– print accuracy (40 μm);

– support for the STL format of the portrait file;

– accuracy of geometry on the manufactured sample.

The following parameters were adopted for printing the blade sample (Fig. 5):

– printing temperature, 210 °C;

– table temperature, 60 °C;

– the thickness of the print layer, 0.2 mm;

– wall shell consist of 2 layers (0.8 mm);

– thickness of the bottom and top: 4 layers (0.8 mm);

– filling of the internal cavity, 15 %;

– automatic generation of supports with an indent of 0.2 mm from the surface to facilitate its removal without damaging the main sample;

– printing speed, 60 mm/s;

– total printing time, 6 hours 15 minutes.

Therefore, the dimensions of the blade sample were proportionally reduced to the size of 25 % of the original and were 150×100.571×57.763 mm in comparison with the actual dimensions of the blade – 640.632×429.527×246.698 mm.

Fig. 6 shows a printed sample of the blade in a reduced size.

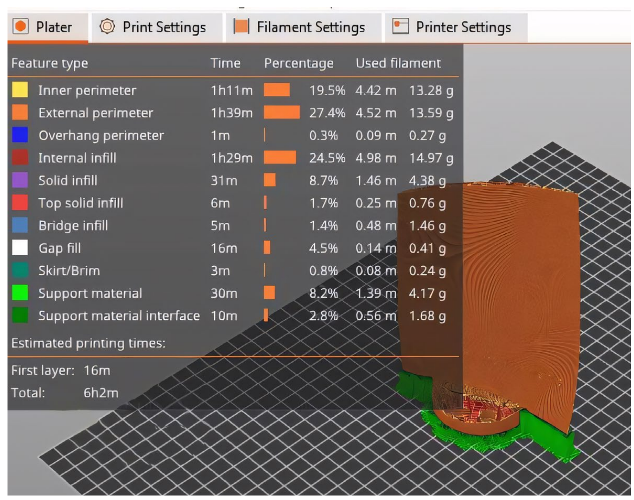
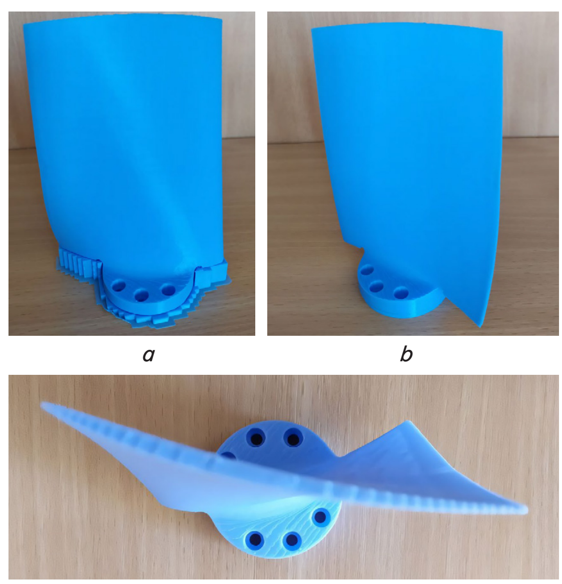


Fig. 5. Selecting options for printing a blade sample



a *b*

c

Fig. 6. A sample of the pumped hydroelectric power plant blade in reduced size, made by 3D printing: *a* — with supporting structures; *b* — without supports; *c* — top view

The next study involved a comparison of the obtained geometry of the printed sample with its ideal portrait. For further inspection using the portrait of the blade sample in a reduced format, it was performed the same proportional reduction of the dimensions of the ideal portrait using the «Transformation Tool» of the Geomagic Design X software. The process of comparing the portraits is shown in Fig. 7.

The following ranges of deviations were obtained when comparing the geometry of a portrait from a reduced sample made by 3D printing with an ideal one:

– convex surface: –0.002...–0.086 mm and 0.004...0.091 mm;

– concave surface: –0.021...–0.46 mm and 0.013...0.059 mm;

– cross section of a convex surface with a cylindrical shank: –0.57...–0.79 mm;

– cross section of a concave surface with a cylindrical shank: –0.055...–0.067 mm;

– rear edge from the side of the convex surface: –0.015...–0.098 and 0.009...0.120 mm;

– rear edge from the side of the concave surface: –0.010...–0.039 mm and 0.053...0.084 mm;

– front edge from the side of the convex surface: 0.004...0.056 mm;

– front edge from the side of the concave surface: 0.014...0.040 mm;

– holes: –0.051...–0.123 mm;

– other surfaces and plane intersection radii: –0.006...–0.079 and 0.044...0.112 mm.

It should be noted that authors of this study are not aware of the value of geometric accuracy for the manufactured part, so it was made a decision to use reference data generally accepted in mechanical engineering. Thus, according to the reference book [19], in the absence of technical specifications on tolerances of form, orientation, location and run-out, such deviations are limited by the tolerance field for the rated size of the part and sample. It is assumed that the blade for the pumped hydroelectric power plant is made according to the 12th quality of accuracy. Then, for a blade sample in a reduced size (4 times the original), the tolerance field for the manufactured part was 0.25 mm, and for the original dimensions of the part – 0.6 mm.

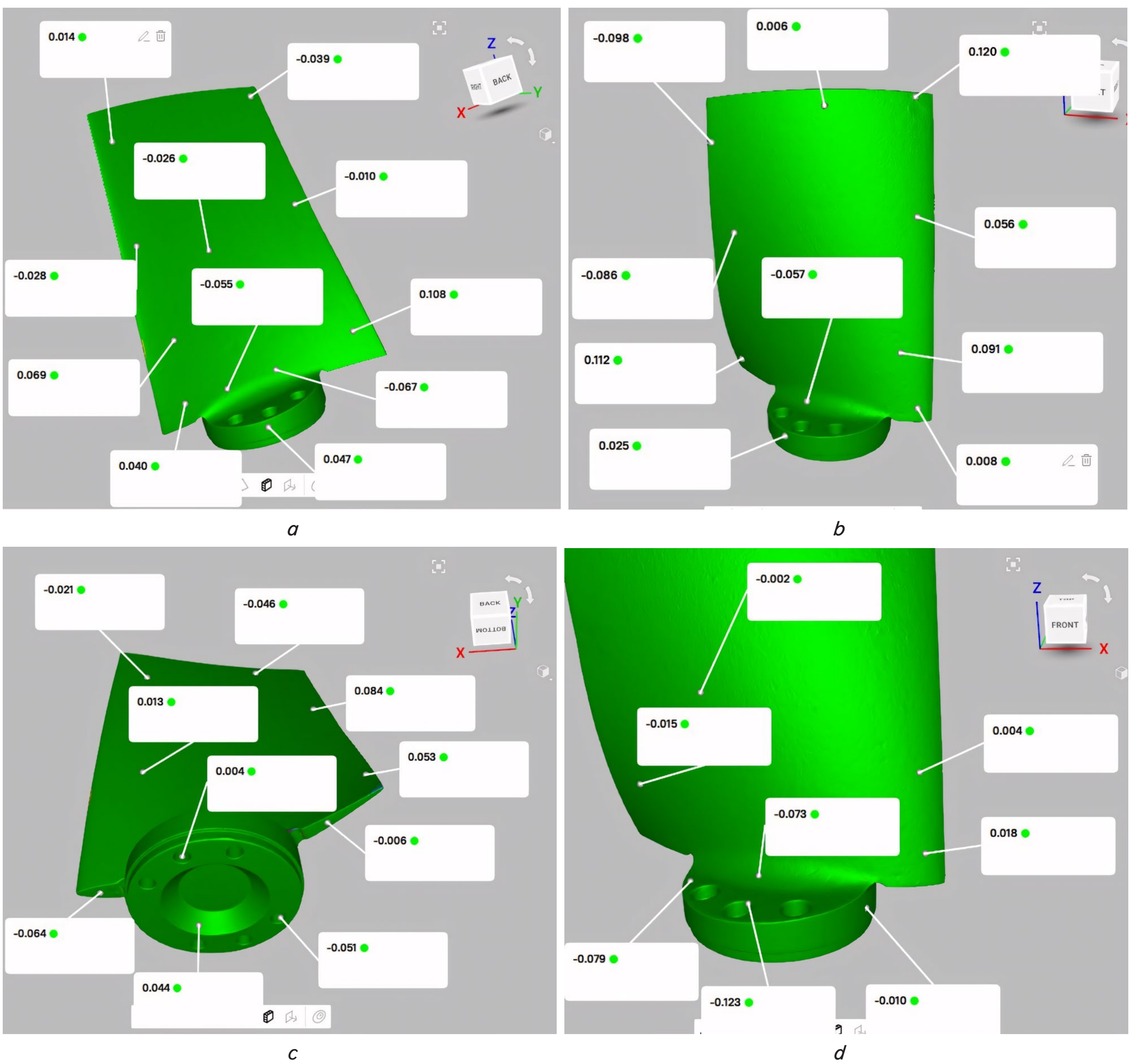


Fig. 7. Inspection and comparison of a portrait of a blade sample in a reduced format with an ideal one: *a* – from the side of the concave surface; *b* – from a convex surface; *c* – in the zones of the holes; *d* – in the zone of intersection of planes

6. Discussion of results of research on devising a methodology for prototyping convex-concave aircraft parts using reverse engineering technology

In this study, a portrait of a physically existing blade for a pumped hydroelectric power plant (Fig. 1) was built in the STL format, taking into account the accuracy provided by the ARTEC Leo scanner (Table 1), which allows to obtain the geometry and shape with an accuracy of ±0.1 mm. It should be noted that in comparison with contact methods of inspection in [10, 11], the non-contact method, based on scanning, does not require special production conditions and allows performing the work directly at the location of the part.

By using a number of Geomagic Design X software tools, the acquired portrait of the blade was refined into an ideal one. The resulting ideal portrait in STL format was reduced to 25 % of the original dimensions, which allowed to reduce the time for 3D printing and the amount of material used.

Control over the 3D-printed blade sample in reduced size was performed by comparing the geometry of the portrait obtained from it with the correspondingly reduced ideal portrait. Proportional reduction of the ideal blade portrait in the STL format in the Geomagic Design X software allowed to preserve the geometry and shape. The resulting experimental studies of scanning a blade sample in reduced size and comparison with an ideal portrait showed that the deviations are from –0.123 to +0.120 mm, which is within the defined tolerance field of 0.25 mm according to [19]. It should be noted that the size tolerance depends on the parameter of relative geometric accuracy, the rated size of the part, and the quality of the accuracy of the part's manufacture.

The experiment showed positive results regarding the proposed methodology for prototyping convex-concave parts of the aircraft, and the inspection results were considered as reliable and adequate in comparison with the data reported in [15].

In contrast to the complete technological chain of prototyping by reverse engineering, as given in [2], it was established that the refined, ideal STL portrait (Fig. 4), could be used to manufacture a part using additive technologies. Moreover, this study allow to perform the preliminary approbation and inspection of the ideal portrait STL for its use in additive or extractive production, provided that satisfactory accuracy of the part's manufacture is obtained.

A peculiarity of the proposed methodology for prototyping convex-concave MEO parts is the use of a portrait from the original part without additional stages of DMU construction. Solving such a task involves the restoration of geometry and shapes of any size, provided that a 3D scanner and/or a CMM suitable for its characteristics are used, where the technology according to the recommendations of the work can also be used [13]. But comparing the amount of information of DMU and the portrait of the experimental part shows that the latter one contains information exclusively on geometry and shapes. The possibility of manufacturing a part according to the ideal portrait obtained from it by additive technologies complements work [14]. Note that in this case, the decisive criterion is either the geometric accuracy or the tolerance field for the size of the manufactured part.

Based on the proposed prototyping methodology, it is possible to test the virtual technique of reverse engineering in order to establish its feasibility and adequacy, which is reported in paper [16]. The expediency of shortening the technological chain of prototyping is also dictated by the complexity and limitations of DMU constructing, which is reasonably substantiated in [17].

The methodology for prototyping convex-concave MEO parts with the provision of the specified geometric accuracy for the manufacture of the part allow to implement quickly the reverse engineering solutions for the reconstruction of not only the portrait but also the DMU of the MEO part.

Implementing the methodology of prototyping based on an ideal portrait allows to combine a number of solutions based on it, namely:

– to solve the task of prototyping parts, as given in studies [18];

– to use an ideal portrait as the primary source of information, as suggested in work [19].

The use of an ideal portrait in production can be recommended in the following cases:

– when implementing sustainable reverse engineering for large-sized parts;

– to inspect the geometric accuracy of the part manufactured by additive or extractive technologies in the case there is no DMU;

– in the case of the need for rapid prototyping of parts for the repair of MEO.

Simplicity of the proposed methodology is that it is possible to perform preliminary approbation and inspection of ideal portraits for parts of any size by using proportional size reduction. However, when inspecting an ideal portrait and a one obtained from a printed sample, it should take into account the obtained rated size and the quality of the sample's manufacturing accuracy, which is sufficiently shown in work [21]. The latter will affect the positivity of the obtained measurements and decision-making to allow the part into production based on an ideal portrait without additional stages of DMU construction.

The disadvantage of using the prototyping methodology will be the impossibility of compiling design and technological documentation, which requires the construction of a DMU as the primary source of information. However, in turn, an ideal portrait will provide an opportunity to increase the accuracy for the construction of DMU, which, in turn, affects the accuracy of the production of the original part. And if there is a need for rapid prototyping of the part using additive or extractive technologies within the tolerance for the size of the manufactured part from ±0.6 mm or more, this approach becomes indispensable. Thus, the obtained results will be useful for improving the existing technologies for manufacturing and prototyping of MEO parts.

Further studies should focus on complex-profiled MEO parts, as well as on the data set from the tolerance field for the rated dimensions of the reduced sample and the manufactured part which has no design and technological documentation for.

7. Conclusions

1. It was found out that the blade had a convex-concave shape with a variable profile, that is, a double curvature, and a connecting shank with identical cylindrical through holes of different diameters, as well as 90° angles and filleting radii in the holes (up to 4 mm). The design and technological analysis of the blade for the pumped hydroelectric power plant allowed to choose an ARTEC Leo (Luxembourg) 3D scanner with a scanning accuracy of 0.1 mm and a resolution of up to 0.2 mm. Such characteristics met the requirements for the field of tolerances for the rated size of the experimental part

and allowed to build a portrait of the blade without unnecessary efforts and the use of additional software tools.

2. It has been proposed to finalize the acquired portrait of the blade for the pumped hydroelectric power plant into an ideal one using the standard tools from the Geomagic Design X software. This allowed to increase the accuracy of the geometry of the STL format file, which in turn affects the accuracy of the DMU construction. A peculiarity of this solution is that manufacturers could use exactly the ideal portrait in the STL format in case of the need for rapid prototyping of the part during the repair of MEO. In this case, the technological chain of production is significantly shortened (at the stage of building a DMU), which reduces the cost of both the single part itself and the whole product.

3. When analyzing data on the technical characteristics of the selected CREATBOT F430 (CHINA) 3D printer, the rated dimensions and the field of tolerances for the manufactured part, it was decided to reduce the dimensions of the sample for printing to 25 % of the original values. For the purity of the experiments, it was assumed that the blade for the pumped hydroelectric power plant was made according to the 12th quality of accuracy. This allowed to establish a tolerance field for the manufactured part of 0.6 mm for the original dimensions and for its sample of reduced size of 0.25 mm. Inspection of the printed sample and comparison with the correspondingly reduced ideal portrait revealed a deviation from –0.123 to +0.120 mm, which is within the defined tolerance field for the manufactured reduced sample. Such results confirmed the adequacy of the proposed prototyping methodology and provided the verification of theoretical foundations of reverse engineering for convex-concave parts of any large size by using a proportional reduction in the size of ideal portraits. The use of full-scale samples in reduced sizes based on ideal portraits of experimental MEO parts will allow manufacturers to reduce costs and to short the time for technological preparation for the production of an original part.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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