ISSN 2664-9969

UDC 629.7
DOI: 10.15587/2706-5448.2024.297732

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MATHEMATICAL MODELS CREATION FOR CALCULATING DIMENSIONAL ACCURACY AT THE CONSTRUCTION STAGES OF AN ANALYTICAL STANDARD USING THE CHAIN METHOD

The object of research is the process of forming a mathematical model (MM) for calculating accuracy at the stages of construction an analytical standard (AS) using the chain method, the application of which is shown on the example of an aviation object (AO). The analysis of the investigated AO, namely the helicopter stabilizer, was carried out using modern 3D scanners and the creation of its analytical portrait (AP). The problem is to create the most similar AP and compare it with AS, taking into account the results of the calculations. The following results were obtained: the AS was built and the AP of the stabilizer geometry was created, a comparative analysis of the AP and AS was carried out, and the results of the accuracy of the object geometry calculations were obtained. Aerodynamic calculations of stabilizer characteristics were also carried out, analysis of standardized aerodynamic profiles was carried out taking into account the accepted limitations for forming the stabilizer AS. The scientific and practical novelty of the obtained results is as follows: the created MM for calculating the accuracy of the dimensions of the unit contour using the chain method made it possible to estimate the tying errors that occur when using the loft-template method. This made it possible to choose equipment and software for construction the AS stabilizer. The selection of improved values of the object's aerodynamic characteristics made it possible to build an AS based on the standardized NACA 0012 profile. This can be used as an information basis for the organization of small-scale production of the object under study. That is, in general, the process of reverse engineering made it possible to conduct a detailed analysis of sections, aerodynamic characteristics and improve them for the future improved profile. This design approach provides wider opportunities, eliminates intermediate links and maintains high accuracy of object parameters during its manufacture, which is one of the main requirements in aircraft construction.
Keywords: *loft-template method, reverse engineering, aerodynamic profile, analytical portrait, dimensional chain.*

Received date: 15.12.2023
Accepted date: 30.01.2024
Published date: 09.02.2024

How to cite
Vorobiov, I., Maiorova, K., Voronko, I., Skyba, O., Komisarov, O. (2024). Mathematical models creation for calculating dimensional accuracy at the construction stages of an analytical standard using the chain method. Technology Audit and Production Reserves, 1 (1 (75)), 26–34. doi: https://doi.org/10.15587/2706-5448.2024.297732

1. Introduction

Different approaches are used during the design and manufacture of aircraft assemblies (AA) [1–3]. In this case, it is interested in the loft-template method (LTM) and reverse engineering.

LTM uses a single system of shapes and sizes to create and geometrically connect structural elements. It is based on a theoretical blueprint of the aircraft assembly, which defines the dimensions and shapes of all relevant parts. The main goal is to ensure the compatibility and accuracy of the connection of elements [4, 5].

Reverse engineering is a process of reverse development, which includes the analysis of the structure and operation of the finished product to create an analytical standard (AS) or model. This method is used to study and reproduce the design and functionality of the object based on the finished sample. This allows to correct flaws or improve an existing product by creating an accurate model of the product [6–8].

When connecting elements and ensuring the operability of the structure, the accuracy of the contour is important, therefore, the reduction of errors becomes a critical aspect in the process of designing and manufacturing an aviation object (AO).

Circuit errors in LTM can be caused by various factors, for example:

– the accuracy of manufacturing templates and forms. Even small deviations during the manufacture of templates can lead to the accumulation of errors in the finished structure;

– deformations of materials. During the processes of assembly and operation, materials can undergo deformations, which can also make changes to the contour and accuracy of elements;

– the instability of the manufacturing process. Changes in manufacturing conditions, technical problems or unforeseen factors can affect the accuracy of the design.

Unit reengineering can significantly affect the process and quality of small-scale production of aircraft equipment, help reduce or avoid contour errors. The main ways to achieve this are as follows:

– analysis and optimization of production processes. When reengineering the unit, it is possible to revise production methods, choose more accurate or modern technologies for manufacturing parts. For example, computer numerical control, additive manufacturing, and other precision techniques can be used;
– improvement of materials and technologies. Consideration of new materials or improved technologies can help eliminate the drawbacks associated with contour errors. The use of more stable and durable materials can also reduce the likelihood of deformations or deviations in the product;
– accurate models and documentation. Creation of accurate ASs and documentation based on reengineering allows for more accurate control of the production process and manufacturing of parts with smaller errors;
– quality control at all stages. The implementation of strict quality control methods in the production process will help to detect and eliminate errors in the early stages, before they become critical to the quality of the final product.

So, it is possible to apply modern reverse engineering technology to reconstruct an existing object, while focusing on improving its theoretical outline.

The aim of research is not only to create a mathematical model for calculating the accuracy of dimensions at the stages of AS construction using the chain method, but also to create a mathematical model for assigning errors when creating an AS stabilizer based on reverse engineering.

2. Materials and Methods

2.1. The object of research. *The object of research* is the process of forming a mathematical model (MM) for calculating accuracy at the stages of AS construction using the chain method. MM takes into account all the errors that may occur during the manufacture and tying of the contours of nodes or aggregates at LTM. The application of this model is shown on the example of an aircraft stabilizer (Fig. 1). Previously, the object was designed and manufactured using the LTM, which resulted in inevitable shortcomings, for example, the accuracy of the implemented theoretical stabilizer circuit. The AS creation on the basis of reverse engineering becomes the first priority. Two Artec scanners Eva Lite and Leo will be used in the work (Fig. 2). After creating the AS stabilizer, it is necessary to perform the necessary calculations of possible deviations from the established aerodynamic contours.

Fig. 1. Experimental aviation detail of the external circuit (stabilizer)

a *b*

Fig. 2. Artec Group (USA) scanners: *a* – Eva; *b* – Leo

2.2. Calculation of the accuracy of the geometric parameters of the stabilizer leading edge circuit during assembly. A preliminary examination of the stabilizer of the aircraft made it possible to establish that its assembly was carried out in a slipway based on the surface of the frame and using the loft-template method of tying.

Assembly based on the surface of the frame is a process in which the contours of the parts of the previously assembled frame are the basis for the contour-forming elements of the assembled assembly unit (AU).

With this method of basing, the cladding is installed with the inner surface on the support surfaces of the assembled frame and is pressed with cutters, tapes or cords. In this case, the errors of the contour-forming elements of the frame are completely transferred to the contours of the finally assembled product. Therefore, it is necessary to strive for the maximum accuracy of the contours when assembling the frame, since it is impossible to correct the errors that have occurred during the installation of the cladding. Basing from the surface of the frame is used when assembling light and medium-class aircraft units, compartments of non-paneled construction, consisting of monolithic and prefabricated ribs and frames.

Let's build a dimensional chain and consider the possible values of errors at the stages of manufacturing and assembly of the stabilizer. The diagram of the formation of the deviation of the actual position of the contour from the theoretical one for the stabilizer frame (sketch of the combined cross-sections of the contour-forming parts of the stabilizer frame and the contour fasteners in the slipway) is shown in Fig. 3.

The constituent links of the main dimensional chain will be: the distance between the axis of the construction plane of the stabilizer (BPS) of the aircraft and the axis of the assembly hole AH in part 1 (A_1), the distance between the contour of part 2 and the AH in this part (A_2), the thickness of the skin S (A_3).

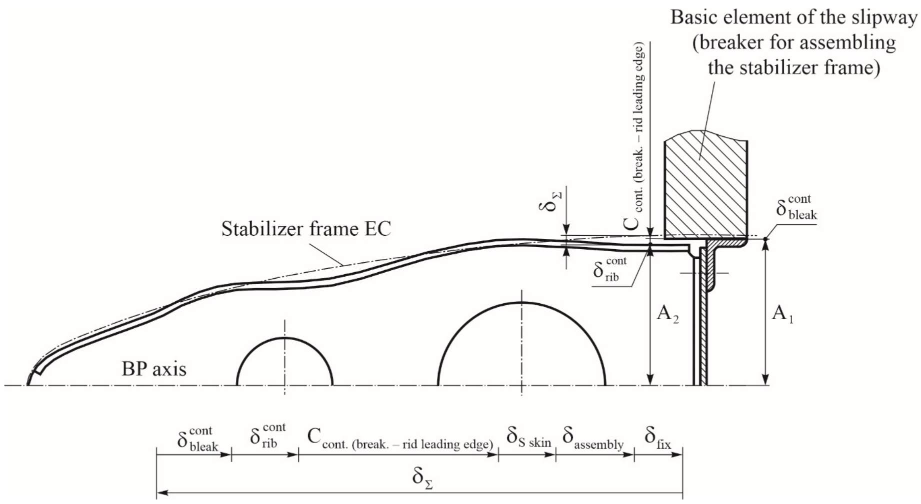

Fig. 3. Sketch of combined cross-sections of contour-forming parts of the stabilizer frame and contour fasteners in the slipway

The amount of deviation of the actual position of the stabilizer circuit from the theoretical one is equal to the error of the closing link A_Σ of the main dimensional chain, which is determined by the formula:

$$\delta_\Sigma = \delta^{cont.}_{break.} + \delta^{cont.}_{leading\ edge.} + \\ + k_{f.} \cdot C_{cont.(break.-rib\ leading\ edge)} + \delta_{S_{skin}} + \delta_{assembly}, \quad (1)$$

where $\delta^{cont.}_{break.}$ – the error of size $A1$ of the installation of the contour retainer (cutter) of the slipway of the stabilizer frame assembly; $\delta^{cont.}_{leading\ edge}$ – the error of size $A2$, which arises as a result of inaccuracy in the manufacture of the stabilizer leading edge rib; $C_{cont.(break.-rib\ leading\ edge)}$ – the error of tying the contours of the cutter and the rib leading edge, which can be reduced by using clamps (taken into account by the fixation coefficient $k_{f.}$); $\delta_{S_{skin}}$ – the error of the skin thickness, according to [9] the thickness of a sheet of normal accuracy for the manufacture of the stabilizer leading edge skin is 1.2–0.15 mm, i. e. $\delta_{S_{skin}} = 0...-0.15$ mm; $\delta_{assembly}$ – the error of the stabilizer circuit, caused by the deformation after the connection, which during AU assembly. Unit of classification group IX is $\delta_{assembly} = (0.1...0.2)\delta_\Sigma$ [4, 10, 11].

The coefficient of fixation during assembly in the slipway is determined by the formula:

$$k_{f.} = 1.5 \cdot \left(\frac{L}{L_{f.}}\right)^{-1.05}, \quad (2)$$

where L – the maximum overall size of AU; $L_{f.}$ – the distance between the fasteners, i. e. $k_{f.} = 1.5 \cdot (750/210)^{-1.05} = 0.394$.

As for the errors, $\delta^{cont}_{break.}$, $\delta^{cont.}_{rib.}$ and $C_{cont.(break.-rib\ leading\ edge)}$, then for their calculation it is necessary the auxiliary dimensional chains, which take into account the tying method used in the technological preparation of production (TPP).

With the adopted loft-template method (LTM) of tying, these dimensional chains have the form shown in Fig. 4. Where the manufacturing errors of the slipway $\delta^{cont.}_{break.}$, the rib leading edge $\delta_{leading\ edge.}$ and the error of tying the rib contours and the slipway fixator $C_{cont.(break.-rib\ leading\ edge)}$.

Calculation of the accuracy of stabilizer assembly and slipway installation is performed using the probabilistic method [4]:

$$\frac{\delta_\Sigma}{2} = t_\Sigma \cdot \sqrt{\sum_{i=1}^{m-1} \xi_i^2 \cdot \lambda_i^2 \cdot \left(\frac{\delta_i}{2}\right)^2};$$

$$\Delta_{o_\Sigma} = \sum_{i=1}^{m-1} \xi_i \cdot \left(\Delta_{o_i} + \alpha_i \cdot \frac{\delta_i}{2}\right), \quad (3)$$

where δ_Σ and $\Delta_{0\,\Sigma}$ – error parameters of the closing link of the dimensional chain (tolerance and coordinate of the middle of the tolerance field, respectively); t_Σ – risk coefficient selected from the tables of values of the Laplace function $t_\Sigma = 1.0$); ξ_i – transmission ratio that characterizes the influence of this stage of size transfer on the final size value (the links that increase $\xi_i > 0$ and those that decrease $\xi_i < 0$ are distinguished; for linear chains $\xi_{increase} = 1$ and $\xi_{decrease} = -1$); δ_i and Δ_{0_i} – error parameters of the input links (component parts) of the dimensional chain; k_i – coefficient of relative dispersion of errors; α_i – coefficient of relative asymmetry of the scattering curve; m–1 – the number of component links (m – the number of size carriers).

Limit deviations of the size are calculated according to the formulas:

$$\Delta_u = \Delta_{0\,\Sigma} + \frac{\delta_\Sigma}{2};\ \Delta_l = \Delta_{0\,\Sigma} - \frac{\delta_\Sigma}{2}, \quad (4)$$

where Δ_u and Δ_l – the upper and lower deviation of the size, respectively.

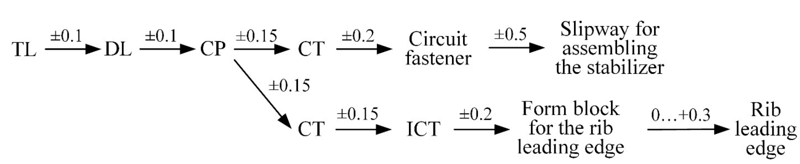

Fig. 4. Dimensional chain for calculating manufacturing and tying errors:
TL – theoretical loft; DL – design loft; CP – control print; ST – surface template; CT – contour template; ICT – internal circuit template

With the normal law of error distribution $k_i = 0$, $\alpha_i = 0$.

The results of the calculation of the manufacturing errors of the rib leading edge $\delta_{rib}^{cont.}$, the installation of the slipway breaker $\delta_{break.}^{cont}$ and the error of tying the contours of the rib leading edge and the slipway breaker $C_{cont.(break.-rib\ leading\ edge)}$ are summarized in Tables 1–3.

The limit deviations of the outer contour of the rib leading edge will be equal to:

$$\Delta_{u\ cont.\ rib} = \Delta_{o_\Sigma\ rib} + \frac{\delta_{\Sigma rib}}{2} = 0.368 \text{ mm};$$

$$\Delta_{l\ cont.\ rib.} = \Delta_{o_\Sigma\ rib.} - \frac{\delta_{\Sigma rib.}}{2} = -0.068 \text{ mm}.$$

The limit deviations of the installation of the slipway breaker will be equal to:

$$\Delta_{u\ cont.\ break.} = \Delta_{o_\Sigma\ break.} + \frac{\delta_{\Sigma break.}}{2} = 0.424 \text{ mm};$$

$$\Delta_{l\ cont.\ rib.} = \Delta_{o_\Sigma\ rib.} - \frac{\delta_{\Sigma rib}}{2} = -0.424 \text{ mm}.$$

The limit deviations of the error of tying the contours of the rib leading edge and the slipway fastener will be equal to:

$$\Delta_{u\ C_{cont.(break.-rib\ leading\ edge)}} = $$

$$= \Delta_{o_\Sigma\ C_{cont.(break.-rib\ leading\ edge)}} + \frac{\delta_{\Sigma\ C_{cont\ break.-rib\ leading\ edge)}}}{2} = 1.08 \text{ mm};$$

$$\Delta_{l\ C_{cont.(break.-rib\ leading\ edge)}} = $$

$$= \Delta_{o_\Sigma\ C_{cont.(break.-rib\ leading\ edge)}} - \frac{\delta_{\Sigma\ C_{cont.(break.rib\ leading\ edge)}}}{2} = -0.78 \text{ mm}.$$

Then, according to (1), the amount of deviation of the actual position of the contour of the stabilizer leading edge from the theoretical position will be equal to:

$$\delta_{u\Sigma} = 0.424 + 0.368 + 0.394 \cdot 1.08 + 0 + 0.15\delta_{u\Sigma},$$

so $\delta_{u\Sigma} = 1.4$ mm;

$$\delta_{l\Sigma} = -0.424 - 0.068 - 0.394 \cdot 0.78 - 0.15 + 0.15\delta_{u\Sigma},$$

so $\delta_{l\Sigma} = -1.1$ mm.

The expected (calculated) error does not exceed the tolerance value for the outer contour of the stabilizer ($[\delta_{stab}] = \pm 2$ mm [12]), i. e. assembly in the slipway based on the surface of the frame with the LTM tying method ensures the specified geometric accuracy.

Table 1

Data for calculating the limit deviations of the outer contour of the rib leading edge $\delta_{rib}^{cont.}$

Link in the dimensional chain	Δ_{u_i}	Δ_{l_i}	Δ_{0_i}	$\delta_i/2$	$(\delta_i/2)^2$	ξ_i	α_i	λ_i	λ_i^2	$\lambda_i \cdot \delta_i/2$	$\xi_i^2 \cdot \lambda_i^2 \cdot (\delta_i/2)^2$
TS – DL	+0.1	–0.1	0	0.1	0.01	+1	0.0	1.0	1.0	0.1	0.01
DL – CP	+0.1	–0.1	0	0.1	0.01	+1	0.0	1.0	1.0	0.1	0.01
CP – CT	+0.15	–0.15	0	0.15	0.022	+1	0.5	1.4	1.96	0.21	0.0441
CT – ICT	+0.15	–0.15	0	0.15	0.022	+1	0.5	1.4	1.96	0.21	0.0441
ICT – form block	+0.2	–0.2	0	0.2	0.04	+1	0.5	1.4	1.96	0.28	0.0784
form block – rib leading edge	+0.3	0	0.15	0.15	0.022	+1	0.2	1.2	1.44	0.18	0.0317
$\delta_{rib}^{cont.}$	–	–	0.15	–	–	–	–	–	–	–	0.2183

Table 2

Data for calculating the limit deviations of the installation of the slipway breaker $\delta_{break.}^{cont}$

Link in the dimensional chain	Δ_{u_i}	Δ_{l_i}	Δ_{0_i}	$\delta_i/2$	$(\delta_i/2)^2$	ξ_i	α_i	λ_i	λ_i^2	$\lambda_i \cdot \delta_i/2$	$\xi_i^2 \cdot \lambda_i^2 \cdot (\delta_i/2)^2$
TS – DL	+0.1	–0.1	0	0.1	0.01	+1	0.0	1.0	1.0	0.1	0.01
DL – CP	+0.1	–0.1	0	0.1	0.01	+1	0.0	1.0	1.0	0.1	0.01
CP – CT	+0.15	–0.15	0	0.15	0.022	+1	0.5	1.4	1.96	0.21	0.0441
CT – breaker	+0.2	–0.2	0	0.2	0.04	+1	0.5	1.4	2.74	0.28	0.1096
breaker – slipway	+0.5	–0.5	0	0.5	0.25	+1	0.0	1.0	1.0	0.5	0.25
$\delta_{break.}^{cont}$	–	–	0	–	–	–	–	–	–	–	0.4237

Table 3

Data for calculating the error of tying the contours of the rib leading edge and the fixator of the slipway $C_{cont.(break.-rib\ leading\ edge)}$

Link in the dimensional chain	Δ_{u_i}	Δ_{l_i}	Δ_{0_i}	$\delta_i/2$	$(\delta_i/2)^2$	ξ_i	α_i	λ_i	λ_i^2	$\lambda_i \cdot \delta_i/2$	$\xi_i^2 \cdot \lambda_i^2 \cdot (\delta_i/2)^2$
CP – CT	+0.15	–0.15	0	0.15	0.022	+1	0.5	1.4	1.96	0.21	0.0441
CT – ICT	+0.15	–0.15	0	0.15	0.022	+1	0.5	1.4	1.96	0.21	0.0441
ICT – form block	+0.2	–0.2	0	0.2	0.04	+1	0.5	1.4	1.96	0.28	0.0784
form block – rib leading edge	+0.3	0	0.15	0.15	0.022	+1	0.2	1.2	1.44	0.18	0.0317
CP – ST	+0.15	–0.15	0	0.15	0.022	+1	0.5	1.4	1.96	0.21	0.0441
ST – breaker	+0.2	–0.2	0	0.2	0.04	+1	0.5	1.4	2.74	0.28	0.1096
breaker – slipway	+0.5	–0.5	0	0.5	0.25	+1	0.0	1.0	1.0	0.5	0.25
$C_{cont.(break.-rib\ leading\ edge)}$	–	–	0.15	–	–	–	–	–	–	–	0.9303

The given results make it possible to evaluate in the process of technical production preparation the deviation of the closed contours of the cross-sections of the stabilizer from the reference cross-sections obtained during assembling in a slipway based on the frame surface using the LTM tying method.

3. Results and Discussion

3.1. Formation of an analytical portrait of the stabilizer. The results of scanning the helicopter stabilizer with a 3D scanner are the initial data for creating an analytical portrait of the geometry (AP) of the stabilizer, which is subject to further comparison with the analytical standard (AS) taking into account the accuracy of the calculations of the geometry of the object. When the geometry of AP and AS coincide, a conclusion is made about the correctness of the choice of manufacturing methods and methods of tying the component parts of the product (CP), means of technological equipment (TE). Otherwise, the causes of errors exceeding the tolerance are revealed, which are eliminated by changing the TE manufacturing methods, replacing the aftermarket, etc., i. e. by adjusting the TP (technological process) of production.

In order to assess the compliance of the obtained APs of the stabilizer with the requirements for the production object, the contours of its cross-sections were digitized (Fig. 5).

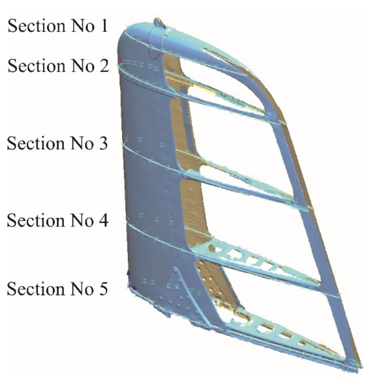

Fig. 5. Sections of the analytical portrait of the stabilizer

The general algorithm for obtaining the geometry of the stabilizer profile is presented in Fig. 6.

The obtained coordinates of the cross-section points of the stabilizer profile are used to assess the accuracy of the data (Fig. 7).

Studies on the digitization of the contours of the stabilizer cross-sections were initially carried out using the Artec Eva 3D scanner, as it was within the immediate reach of the author.

To assess the suitability of the selected method of construction of the AP stabilizer, the scanning procedure was performed four times. The spread of the geometry of the obtained sections was equal to 6.8 mm (Fig. 7).

These values changed both when re-scanning the same stabilizer and when changing the operator, the order of scanning the object, the method of data processing, and the use of different methods of frame tying. The main problems arose during the scanning of the trailing edge of the stabilizer. Obtaining a transition from the upper surface of the stabilizer to the lower relatively sharp edge caused the greatest difficulties in terms of eliminating surface gaps. To increase the accuracy of scanning and reduce the number of defects, various objects with characteristic features of the shape (wooden blocks, lumps of construction tape, etc.) were additionally placed in the scanning area. When scanning the edge parts and ribs of the stabilizer, a contrast substrate was used. Additional lighting was changed to eliminate contrasting shadows.

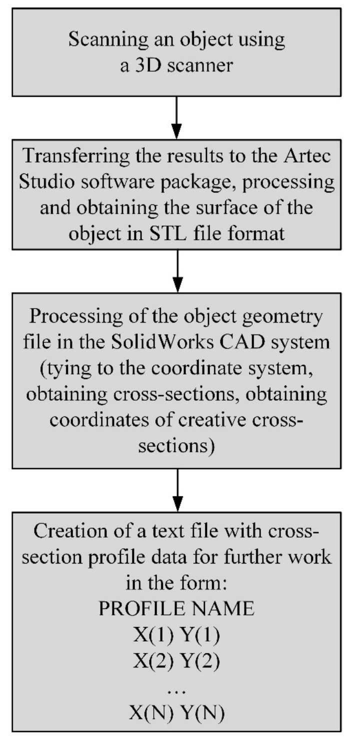

Fig. 6. General algorithm for obtaining the geometry of the product profile

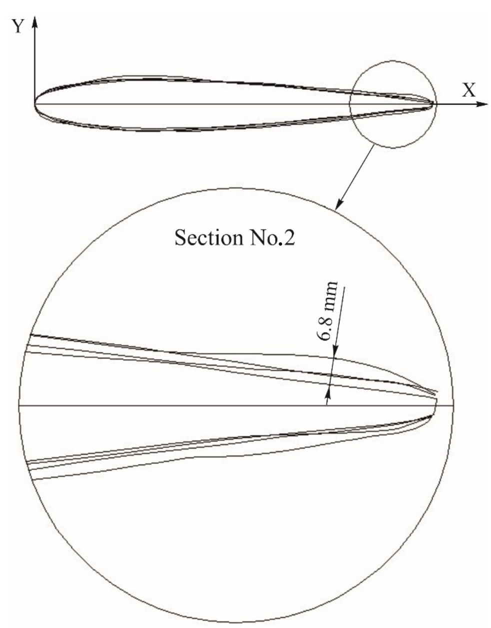

Fig. 7. Results of Artec Eva scanning and contour processing of Cross-Section No. 2

The results obtained in this way clearly demonstrate the existence of a solved problem, but this solution is not the only one. Based on this, it can be argued that the task is incorrectly set according to the second condition. In order to solve the problem, it is necessary to go from an incorrect formulation of the problem to a correct one. Therefore, in order to obtain a satisfactory result when solving the task, the following conditions must be taken into account:

– the accuracy of AP construction is directly affected by the qualification of the performer (operator) of the scanning procedure;
– the technical characteristics of the scanner significantly affect the quality of AP construction.

All subsequent constructions of the AP stabilizer were performed by a highly qualified operator and an Artec Leo scanner with higher technical characteristics than Artec Eva.

Fig. 8 shows the results of scanning the stabilizer with the Artec Leo scanner and processing Section No. 2. The scanning procedure was also performed four times. The scatter of the geometry of the obtained cross-sections turned out to be significantly smaller than the scatter of the Artec Eva scanning results: the deviations were less than 0.5 mm. These values practically did not change during repeated scanning of the object by another operator. Deviations are included in the tolerance on the stabilizer circuit, equal to ±2 mm [12].

Comparative results of scanning by different scanners and different operators can be seen in the footnotes (Section No. 2) in Fig. 7 and Fig. 8.

Based on the results of construction and analysis, a decision was made to use the Artec Leo 3D scanner in the future.

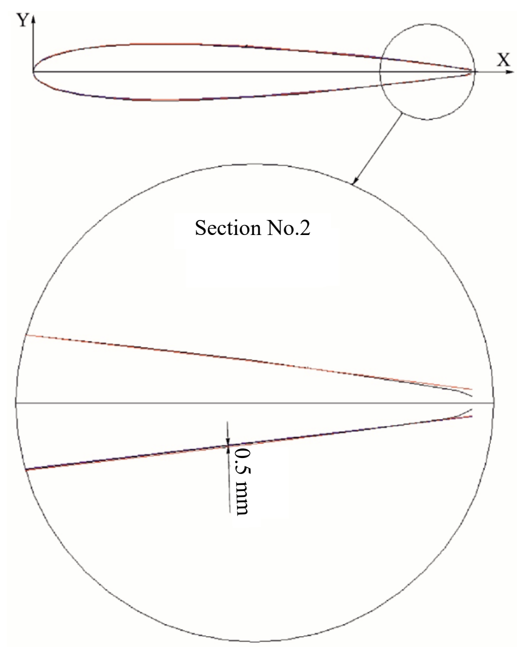

Fig. 8. Results of scanning Artec Leo and processing the contour of the Section No. 2

3.2. Requirements for the accuracy of the analytical sample of the stabilizer. Next, a qualitative picture of the influence of the accuracy of the helicopter stabilizer manufacturing on stability, controllability and the range of operational limitations is considered, which allows establishing additional requirements for the accuracy of the stabilizer AS.

A helicopter stabilizer is designed to provide and improve longitudinal stability, damping and controllability. The problem of helicopter stability is one of the most difficult tasks for improving the flight characteristics of helicopters, and all possibilities for improving the stability and controllability of this type of aircraft are far from being exhausted.

Analysis of stability and controllability is based on solving the equations of motion of the helicopter as a whole.

The simplified efficiency of the stabilizer is proportional to the area of the stabilizer S_{st}, the shoulder of the stabilizer installation L, the derivative of the coefficient of lift at the angle of attack $C^{\alpha}_{y_{st}}$ by the angle of attack α.

According to the characteristics of the poles, it is necessary to evaluate the suitability of the geometry of the stabilizer circuit obtained as a result of scanning for the AP construction of the future production facility. In our case, this is the influence of the geometry of the contour of the section profile on the $C^{\alpha}_{y_{st}}$ behavior α, its value and linearity along the angle of attack α. Also, the quality of the helicopter's flight characteristics and the extension of the flight range are affected by the angle of flow disruption, which in turn depends on the geometry of the profile and its features (sharp, smooth, etc.), as well as on hysteresis when returning from large angles of attack to small ones. After all, these characteristics describe the nature of recovery of lifting force on the stabilizer after flow disruption and largely determine the stability and controllability of the aircraft during its operation. The requirements for the accuracy of the geometry of the units are adjusted by calculating the aerodynamic characteristics of the bearing, stabilizing and control surfaces of the aircraft.

To analyze the aerodynamic characteristics of the stabilizer, it is necessary to obtain a family of its sections along the chord of the ribs by constructing the corresponding AP contours. The obtained coordinates of the cross-section points of the stabilizer profile are used to determine the aerodynamic characteristics of the obtained profiles. The calculation of the aerodynamic characteristics of the aerodynamic profiles that make up the geometry of the stabilizer's outer contours was performed in the XFOIL program [13]. The calculation algorithm is shown in Fig. 9.

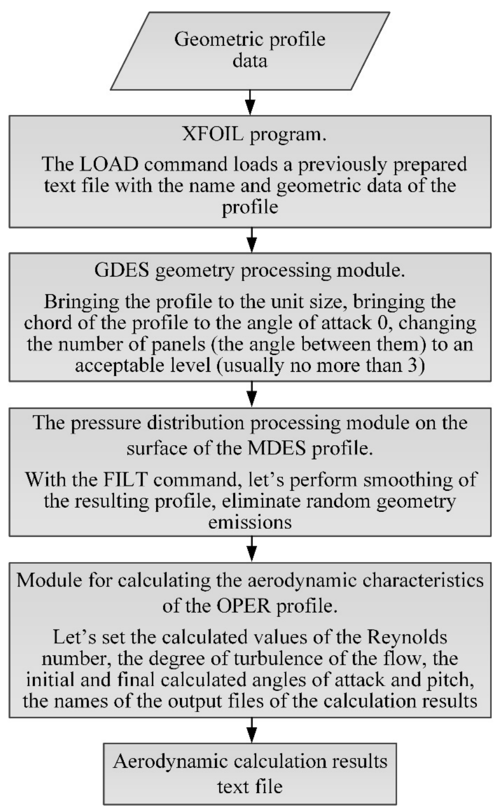

Fig. 9. Algorithm for calculating the aerodynamic characteristics of the profile

In the process of calculations, let's set the Mach number $M=0$, the Reynolds number $Re=1000000$, the flow turbulence criterion $n=4$ (high turbulence). Let's also set the calculated range of attack angles –5...15° and a step of 1°.

3.3. Designing the analytical standard of the stabilizer taking into account the scanning results. The characteristics of stability with a stationary stabilizer and a change in the angle of attack and controllability when the stabilizer is deflected are most influenced by the value of the derivative coefficient of the lift of the wing profile along the angle of attack $C^{\alpha}_{y_{st}}$, the angle of attack at zero lift $\alpha_{C_y=0}$, the maximum coefficient lifting force $C_{y_{max}}$. At the same time, the aerodynamic resistance of the profile and its moment characteristics are not considered.

The maximum lift coefficient of the wing profile $C_{y_{max}}$ affects the range of helicopter centers.

The angle of attack at zero lift force $\alpha_{C_y=0}$ determines the initial angle of stabilizer installation. If it is changed due to manufacturing inaccuracies or deformation during operation, it will be necessary to adjust the angle of installation of the stabilizer.

From the results of scanning and calculation, comparison with theoretical results, it can be concluded that $C^{\alpha}_{y_{st}}$ of the scanned cross-section and the NACA 0012 profile differ slightly and can be neglected.

$\alpha_{C_y=0}$ of the scanned cross-section of the stabilizer and the NACA 0012 profile differs by approximately 1° and, apparently, in real operation, this will practically not affect the stability and controllability characteristics of the helicopter [14].

$C_{y_{max}}$ of the NACA 0012 profile is significantly higher than that of the scanned section of the stabilizer. The dependence of the lift coefficient on the angle of attack is smooth after the critical angle of attack. In the scanned section, the flow disruption is sharper and when piloting the helicopter, this phenomenon can manifest itself in a sharp change in the pitch angle and the development of a catastrophic situation in flight.

From all that has been said, it can be concluded that an increase in the accuracy of performing contours of aerodynamic surfaces will lead to an improvement in the flight and aerobatic characteristics of the helicopter.

According to the above algorithm, the aerodynamic characteristics of AP sections were obtained (Fig. 10, solid red curve).

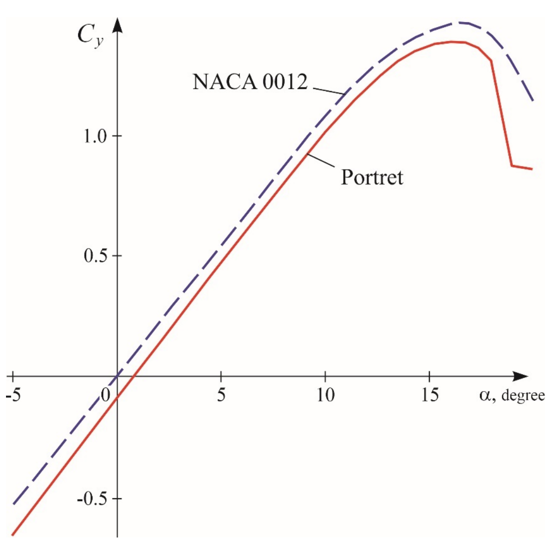

Fig. 10. Dependence of the lift coefficient C_Y on the angle of attack of the theoretical profile NACA 0012 and the section of the analytical portrait (Portret)

A detailed analysis of the scanning results indicated some deviation from the symmetry of the cross-section geometry, and the stabilizer profile is symmetrical in practice of Mil bureau. For this reason, the possibilities of restoring a symmetrical cross-sectional profile within the existing limitations were investigated. As a result, several symmetrical cross-section profiles of the stabilizer were built. For each of them, an aerodynamic calculation of the dependence $C_y=f(\alpha)$ was performed. Analysis of the obtained results showed that the characteristics of the NACA 0012 profile are higher (Fig. 10, dashed blue curve). Fig. 11 shows the procedure for combining the NACA 0012 profile with the AP section of the stabilizer.

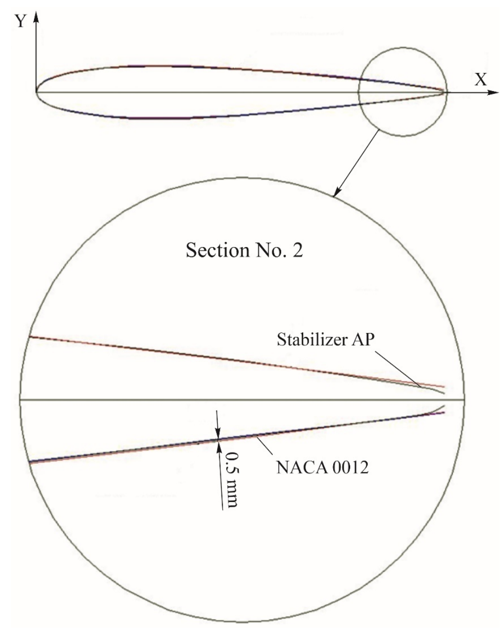

Fig. 11. Combination of AP stabilizer sections and NACA 0012 profile

Based on the NACA 0012 profile, the stabilizer AE (Fig. 12) was built, which became the information basis for the technological preparation of its production.

Fig. 12. Analytical stabilizer standard

3.4. Evaluation of the correctness of the reengineering results of the analytical standard of the stabilizer. Section 2.2 shows the technological chain of assembly operations in the manufacture of a stabilizer using LTM tying, which dominated all Ukrainian aviation industries in the 60s and 80s of the last century. There, the limits of possible deviations of the stabilizer circuit from its standard $\begin{pmatrix}+1.4\\-1.1\end{pmatrix}$ mm were determined. To assess the correctness of the hypotheses and assumptions adopted during the construction of the AS stabilizer, it is necessary to compare the AS with the AP obtained from the results of digitizing the unit.

Since the errors in LTM tying were determined in the cross-sectional plane of the stabilizer, the same procedure must be performed comparing its AS and AP (Fig. 13). From Fig. 13 it can be seen that the contours AS and AP lie in the field of errors of the external contour of the stabilizer when assembling in a slipway based on the surface of the frame and LTM tying.

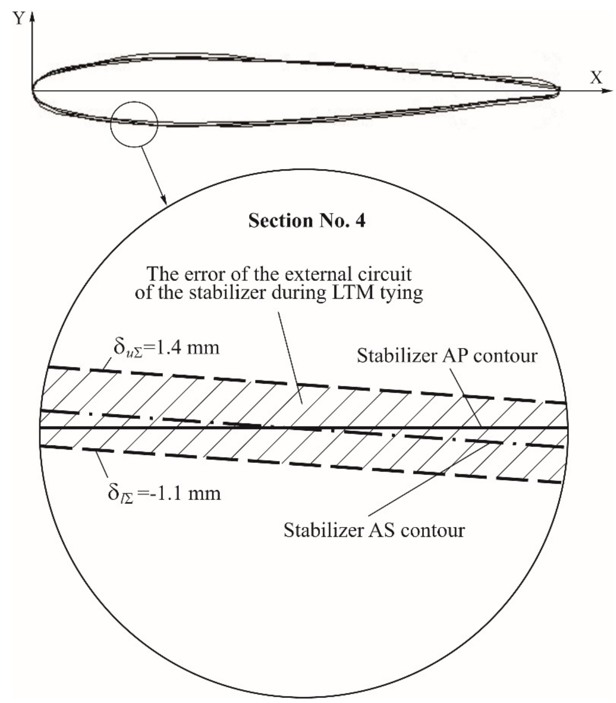

Fig. 13. Comparison of the contours of the analytical standard of the stabilizer (with restrictions) and its portrait in Section No. 4

3.5. Discussion. *Practical meaning.* The results obtained in this way show that this mathematical calculation model can be used for various aviation objects of a similar type. The technology does not require the purchase of bulky and expensive equipment, so it can be quickly implemented in production. Scanning for the AS construction is performed by portable scanners and can be used both in hangars and outside, which simplifies the operator's work with the object. Analyzing the aerodynamic characteristics only requires the presence of the XFOIL program, so the procedure can be performed without complications.

Limitations of the study. For successful practical application in production, it is recommended to first work with a test object to adjust the indicators.

The influence of martial law conditions. The state of war in Ukraine became, in a way, an impetus for accelerating the development of research in the field of reengineering. Aircraft parts fail and require repair or replacement in a short period of time. Also, trophy equipment can be repaired and adopted by the Ukrainian army. Therefore, this direction of research is particularly relevant.

Prospects for further research. In the future, it is planned to manufacture AO using additive technologies and compare the parameters of finished products, for the manufacture of which different approaches are used: the loft-template method and reverse engineering.

4. Conclusions

The task of reengineering the stabilizer of the Mi-2 helicopter in order to organize its small-scale production is inextricably linked with the assessment of unit circuit errors during LTM tying. This information made it possible to choose a scanner and software for construction the stabilizer AS.

Carrying out multiple measurements of the object by the Artec Eva scanner with a certain qualification of the operator made it possible to assess the correctness of the definition of the task. As a result, it was concluded that the original definition of the task was incorrect, which required the replacement of the original scanning device with an Artec Leo and the involvement of a highly qualified operator.

Aerodynamic calculations of the characteristics of the stabilizer, performed using the contours of the sections of the stabilizer AP, made it possible to draw a conclusion about the low values of $C_{y_{max}}$. To increase the value of this parameter, an analysis of standardized aerodynamic profiles was performed, taking into account the accepted limitations for the formation of the AE of the stabilizer.

The AS of the Mi-2 stabilizer was built on the basis of the NACA 0012 profile, which is the information basis for the technological preparation of its production.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

Financing

The research was performed without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

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

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