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EXPERIENCE AND EFFECTIVENESS OF THE NO-LOFT LINKING SHAPE AND DIMENSION METHOD USING LASER OPTICAL SYSTEMS IN AIRCRAFT PRODUCTION

The object of research is the application of the no-loft linking shapes and dimension method using laser measuring tools to reduce the labor intensity and cycle of mounting work. The study of the accuracy of the geometric parameters of cantilever wing and technological equipment at various stages of production was carried out. The problem is to create a method of using laser optical systems in aircraft production at the stage of mounting of technological equipment to minimize the impact on the accuracy of the dimensions of assembled parts of aggregates. The following results were obtained: the advantages of using the no-loft linking method in the modern production of aviation equipment were analyzed, which makes it possible to reduce the preparation cycle by 2–3 times. A study was conducted on the effective use of the Coordinate Measuring Machine (CMM) of laser tracker in the manufacture of the cantilever wing (CW) of the AN series airplane at all stages of mounting, as well as on the accuracy inspection of geometric parameters in comparison with the theoretical master geometry (MG).

The practical significance of the research is that the proposed method of using laser optical systems during the installation of equipment allows to reduce to a minimum the impact on the accuracy of low rigidity frames. And also, to reduce the equipment deformation due to the mass of the parts of the assembled aggregates and temperature deformations, which allows to ensure a reduction of the mounting error to ±0.1 mm. Also, the application of this technique allows to enter the plane's coordinate system without prior leveling, to mounting and inspection the installation of the wing, fin, stabilizer, engines and landing gear on the fuselage. In general, the application of the no-loft linking shape and dimension method with using laser optical systems in aircraft production allows to reduce the labor intensity and cycle of mounting work up to 10 times.

Keywords: *accuracy of aircraft contours, laser means of inspection, aggregate digital mock-up, no-loft assembly method, laser tracker, aircraft leveling.*

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1. Introduction

The design documentation is the main document that sets the requirements for the geometry of the products. And the conformity of the geometry of the real product to the requirements of the documentation is the most important criterion for the quality of aviation products. Unlike simple parts or assemblies, it is not always possible to measure the geometry of complex structures with traditional contact mechanical tools and measuring devices. Since a large percentage of aircraft products are complex assemblies, the inspection problem their geometry poses certain difficulties.

In general, mechanical engineering, the shape of most machine parts is described by combinations of geometric bodies bounded by simple surfaces – flat, cylindrical, conical, spherical, etc. In aircraft construction, the contours of most parts have complex aerodynamic shapes, which is one of the main differences of this type of mechanical engineering.

Known to date, widely used contact and optical means of control, in connection with rapid scientific and technical progress, do not meet modern requirements, and therefore, with their help, it is impossible to achieve the necessary quality requirements of modern aviation equipment.

When using contact means of inspection, the external contours of the aggregates are specified in the form of theoretical tables of abscissas and ordinates, corrected when drawing the external contours on the surface.

Table 1 shows the means of inspection and the inspection errors of the parameters of aviation equipment, which are achieved in this case [1–3].

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Table 1

Parameters of aggregates subject to inspection and means of their inspection

Inspected parameters	Inspection means	Error of the inspection method, mm
Deviation of the inspection ordinates of the real section of the aggregate	The measuring stand, made according to the mounting standard of the aggregate, indicator probe	±0.5
	Measuring stand made in the instrument stand, indicator probe	±1.5–2
	Outline equidistant templates. Wedge probe. Measuring plates	±2.5
	НА-3 or НА-1 level and movable rail	±0.4
	ПСК-2 device for inspection curved surfaces	±0.4
Local defects: a) steps and gaps at the joints of the cladding; b) protrusion and depression of hidden fastening	Indicator device	±0.3
	Plate probe	±0.5

In aircraft production, in contrast to general mechanical engineering, the assembly and mounting of aggregates is done in specialized equipment (jigs) [3–5].

Accuracy and interchangeability of assembly equipment plays an important role in the production of aviation equipment. The most important parts of the equipment are the base elements (locators, fixing arms, connecting plates, fasteners). Ultimately, the accuracy of assembly and mounting of the assembled product depends on the accuracy of their manufacture and installation in the equipment frame. The mounting of base elements depends on the adopted method of assembling the equipment and, therefore, it contributes the largest component to the total error. In the real conditions of aircraft production, it is considered that the stage of installing the base elements in a given position is the most difficult, provided that the permissible error of the base points is within 0.1–0.3 mm [4, 5].

The methods of traditional mounting of jigs are based on the transfer of geometric dimensions to the basic elements using rigid carriers of shapes and dimensions (templates, standards, mock-ups, coordinate instrument stands, etc.).

The mounting of the assembly jig is the most responsible stage of the equipment manufacturing, in the process of which parts and assemblies of the jig are assembled in accordance with the dimensions specified by the drawing. The mounting process is accompanied by the linking of technological equipment and ensuring the necessary assembly accuracy.

Assembly jigs are subject to inspection, both during manufacture and during operation. The inspection method, in turn, depends on the adopted method of mounting of the assembly jig. Until now, in the process of technological preparation of production, depending on the type, dimensions of the product and serial production, one of the dependent methods of assembly and linking of dimensions was chosen.

The most famous are: program-instrumental; program-template; program mock-up. The listed methods differ from each other in the variety and amount of necessary technological and inspection rigid equipment, which transmits, in accordance with the technological process, the specified accuracy of the shapes and dimensions of the assembled aggregate. In this regard, the listed methods are called related (dependent) methods of manufacturing aggregates. In real conditions, as a rule, in the production of products, several methods of co-ordination are used at the same time [5–8].

The listed methods are characterized by the length of the assembly cycle, high material consumption, significant costs and, as a result, low accuracy. Fig. 1 presents a block diagram of dependent methods for co-ordination aggregate dimensions. Analysis of parameters and characteristics of contact means and inspection methods listed in Tables 1 and 2, indicate that traditional methods cannot achieve the required accuracy and quality for modern aviation technology [7–9].

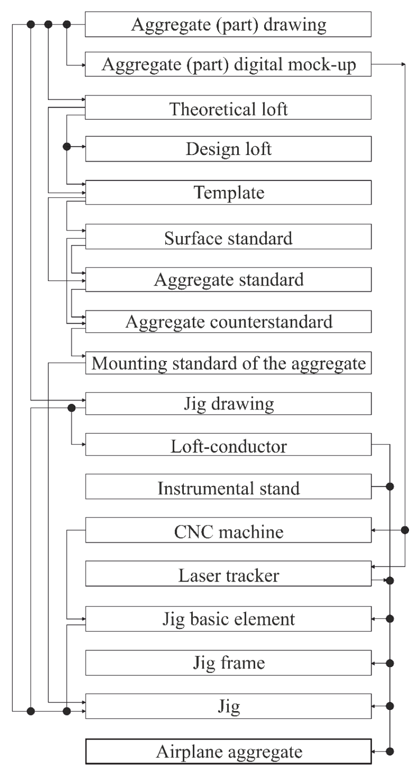

Fig. 1. Block diagram of the method of dependent assembly and linking for dimensions

Table 2

Accuracy indicators (permissible deviations) when mounting assembly equipment using different methods

The method used	Value (mm)	
Jig mounting according to jig templates	Permission to install the template	±2.0
Jig mounting using mounting standards	Accuracy of welding the barrel to the beams	±2.0
Jig mounting using a loft conductor	Tolerance on the step of the bushings for co-ordination the axes of the fastening holes of the fixing elements	±0.2
Jig mounting using an instrumental stand	Tolerance on the step of bushings for mounting of fasteners	±0.2

With the development of the apparatus for mathematical modeling of objects and production processes, as well as the use of electronic computing equipment and CNC equipment, it became possible to independently manufacture parts with a given accuracy sufficient to ensure interchangeability.

The method that implements this assembly process is called coordinate-digital (coordinate-analytical) CDM. The further development of this method with the use of laser optical equipment served as the basis for the development of an independent method of forming the shapes and dimensions of the elements of the connecting structures, and was named the method of no-loft linking (NLL) [7–9].

Therefore, *the aim of research* is to generalize and analyze the experience of using expensive inspection and measurement laser-optical equipment, with the aim of the most effective application at various stages of the creation of aviation equipment.

2. Materials and Methods

2.1. No-loft linking method. *The object of research* is the application of the no-loft linking method of shapes and dimensions using laser optical systems to reduce the labor intensity and cycle of mounting work.

The use in production of modern CAD/CAM/CAE systems, together with laser optical systems, allowed to develop a new method of mounting and ensuring dimensions. This method is based on the use of a three-dimensional model as the primary source of geometric information, with the use of program analytical modeling. A mathematical model is called a design digital mock-up (DDM) or a master model (MM).

The principle of the master model is based on the use of a three-dimensional digital mock-up of the part, which has undergone co-ordination in the environment of the assembly, as a one carrier of geometry and design technology for all subsequent developments of special technological equipment at the same time. Namely, templates, jigs, stamps, work blocks, molds, assembly jigs, etc.

In the future, the digital mock-up makes it possible to perform work in parallel to all participants in the preparation of the production of the product.

The average statistical cycle of putting an aircraft into production based on traditional methods, taking into account assembly and flight tests, to the serial production process is 5–6 years.

Modern production methods, which allow parallel execution of work by all services of the aircraft industry, shorten the training cycle by 2–3 times compared to traditional ones [9].

With an independent method of manufacturing parts with a specified accuracy, sufficient to ensure interchangeability, the need for rigid means of co-ordination the blanking and assembly tooling disappears. Instead of them, coordinate graphs, CNC equipment, laser, optical means of mounting and inspection (for example, a laser tracker) and, if necessary, a loft conductor and an instrument stand are used [8, 10–12].

Fig. 2 shows a block diagram of an independent method of co-ordination dimensions, using a laser optical system.

The developed linking shape and dimension method of products is successfully used at the state enterprise «Antonov» (Ukraine) in the creation and serial production of An-158, An-178, An-132 aircraft.

This method covers all stages: design, technological preparation and production of products.

Laser devices for measuring geometric parameters (LMGP) can function on different principles that realize certain properties of laser radiation due to its coherence [12]. These systems have high accuracy and productivity in combination with non-contact measurement method and digital form of presentation of results.

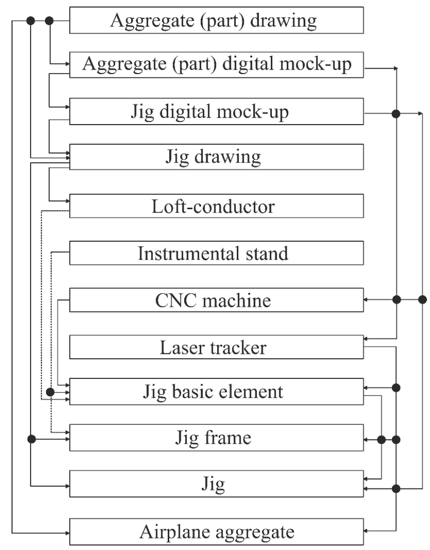

Fig. 2. Block diagram of the no-loft (independent) co-ordination

The LMGP advantage is compactness, they can easily be brought closer to the object to be measured and placed in the workshop, unlike, for example, coordinate measuring machines, the action of which involves placing the measured object on their table.

At the stage of designing technological equipment, when using the method of no-loft linking, it is necessary that the aerodynamic surfaces of the aggregates are determined by typical analytical methods.

In preparation for production, the no-loft linking method using a laser tracker allows to achieve:

– deviation of dimensions and location of surfaces during mounting of jig equipment – from 0.1 to 0.2 mm;
– dimensional deviations when creating basic holes in frame parts – up to 0.1 mm;
– deviation of the shape of contour-forming surfaces – from 0.1 to 0.5 mm;
– reduction of the need for the production of templates and other rigid dimension media – up to 30 %;
– reduction of the cost of manufacturing jig equipment.

Currently, laser computerized systems of the FARO LaserTracker type are successfully used in the aerospace industry, which have a working area of measurements in a linear measure of up to 100 m, and in an angular measure – up to 270 degrees in azimuth and at least ±50 degrees in elevation. Distance measurement errors at distances of about 1 m are up to 10 μm, and the error of angular measurements does not exceed 10 minutes.

The principle of operation of the laser tracker consists in the measurement of two angles α, β and the distance d (Fig. 3).

One of the distinguishing features of the tracker is the automatic control of the angular coordinates of the emitted beam. For this, the tracker sends a laser beam to a light-reflecting reflector (benchmark), which touches the surface of the object being measured. Part of the light reflected by the benchmark enters the distance meter, which calculates the distance from the tracker to the reflector. The distance meter can be of two types: an interferometer (IFM) or an absolute distance meter (ADM).

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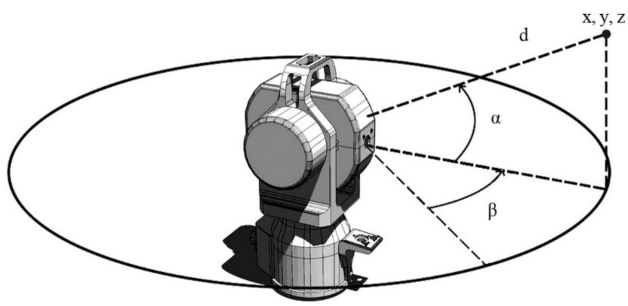

Fig. 3. The principle of determining coordinates using a laser tracker

The laser tracker contains two head rotation angle sensors (encoders). These devices measure the angular orientation of the tracker's two mechanical axes: the azimuth axis and the elevation axis. The angles obtained from the encoders and the distance from the distance meter are sufficient to accurately determine the position of the center of the retroreflector. Trackers allow high-precision measurement of geometric primitives (points, circles, planes, cones, cylinders, etc.), the distance and angles between them, deviations of form and mutual location. It is also possible to control complex curved surfaces by comparing with a CAD model.

Correct positioning can be carried out by known coordinates or linear-angular dimensions. It is possible to reduce time by using the method of comparison with the CAD model of the structure. This reduces the time for reconfiguration and launching a new product into production. Modern trends in the application of classical interferometric schemes consist in the recording of interferograms by matrix photoreceptors, followed by input of spatial distributions of intensity in a computer and automated processing of recorded digital images.

The use of universal laser optical measuring systems, such as the Laser Tracker, allows to solve various tasks of monitoring production facilities, both during the creation and further maintenance of serial production.

Such objects include, at the stage of technological preparation of production, the inspection of the production of templates, standards, mock-ups, stretching punch, blanks, form blocks, locators (Fig. 4), blanks for laying out (Fig. 5), stamps and jigs (Fig. 6, 7).

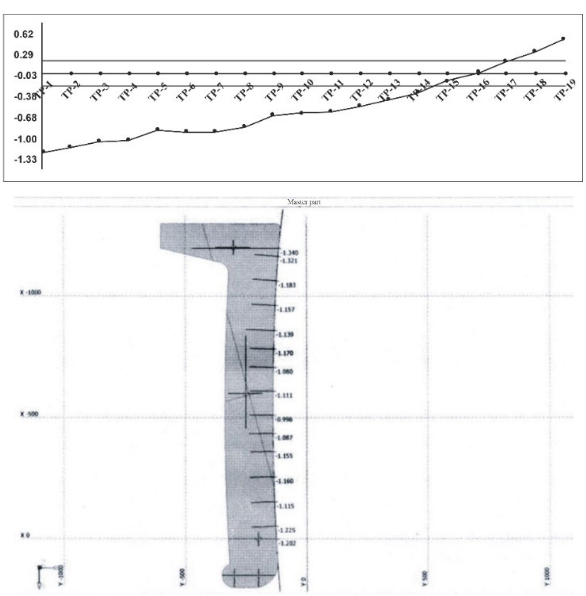

Fig. 4. The result of control of the contour-forming element (cut-off) of the wing assembly jig with a laser tracker

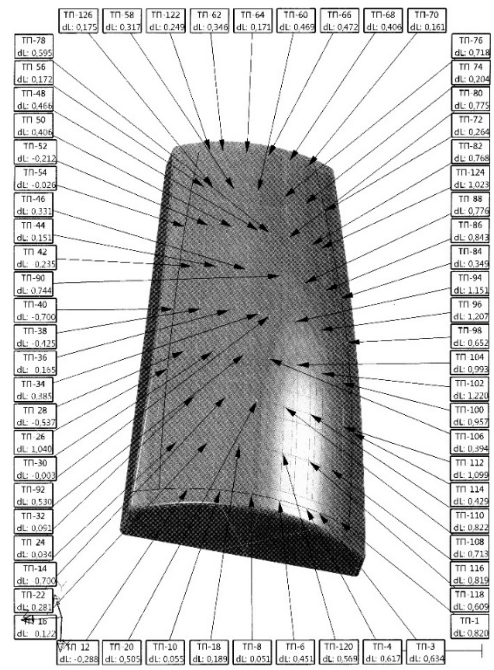

Fig. 5. A blank model for laying out with an indication of deviations from the theoretical profile at characteristic points measured by a laser optical system

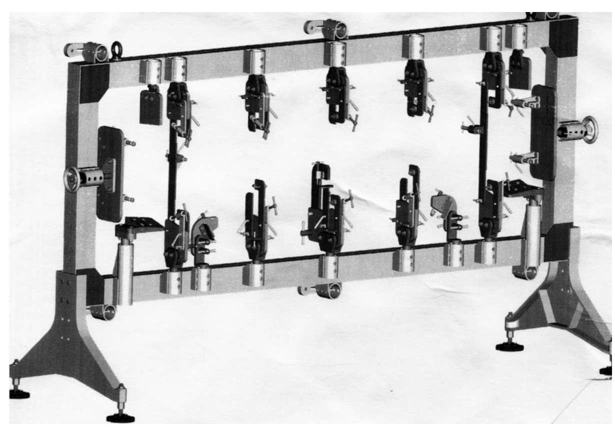

Fig. 6. General view of the jig for assembly of the first spar (design electronic model)

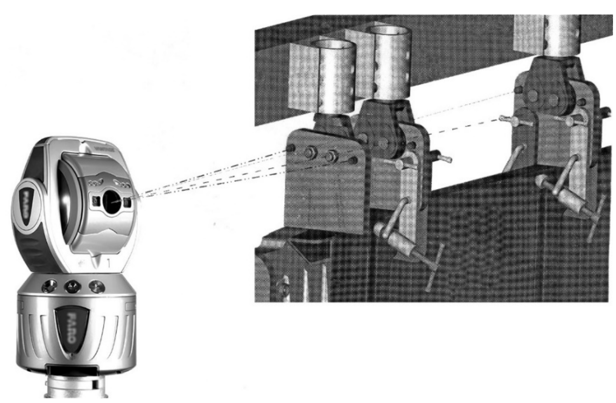

Fig. 7. Installation and inspection of jig elements using a laser optical measuring system

At the production stage, inspection of the manufacture of parts, assemblies, aggregates, mounting and leveling of the aircraft is carried out.

2.2. Study of the accuracy of the geometric parameters of the cantilever wing and technological equipment at various stages of production. Below is an example of the effective use of the Laser Traker CMM in the manufacture of the cantilever wing (CW) of the AN product at all stages of its assembly and inspection of the accuracy of geometric parameters in comparison with the theoretical master geometry (MG).

The task of research during leveling: checking the contour-forming characteristics of the jig and waiting for the actual parameters after assembling the aggregate in it.

When using the traditional method of leveling the plane, the following were used: a level of accuracy class 3, a leveling ruler, a tape measure, and a building height [12, 13]. The average error when removing the dimensions from the leveling tool was 0.5 mm. The error of setting the leveling ruler was from 0.5 to 1 mm.

In general, the measurement error of an independent parameter of one leveling point reached 1.5 mm. The excess of two measured points, relative to each other, could reach up to 3 mm, while according to the passport and the leveling drawing, the tolerance for exceeding the reference points is usually 1 mm.

Reference points on the fin, located on surfaces close to the vertical, are practically impossible to measure, since the level measures only the excess relative to the horizontal plane.

The experience of leveling and operation of An-148, An-158 aircraft showed that changing the geometric parameters of modern aircraft within the range of errors determined using the traditional leveling method affects the flight characteristics of the product.

The volume of information obtained during the inspection of the geometric parameters of the aircraft with the help of a level is insufficient for the analysis of the actual three-dimensional measurements.

At the current stage of production of AN products, a similar inspection system is implemented using FARO Laser Tracker Vantage type optical equipment. This method of controlling the real shape of the surface of large-sized products of complex shape is a coordinate-determining inspection technology that allows to calculate the necessary geometric parameters of the aircraft being measured (Fig. 8).

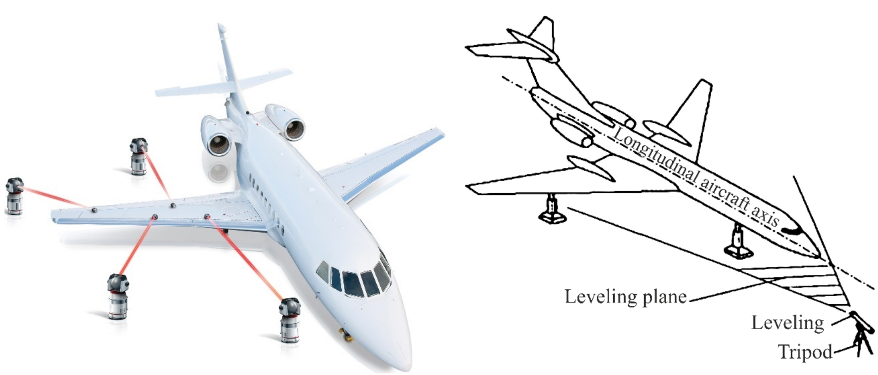

Fig. 8. Geometry inspection (*a*) and plane leveling (*b*)

The process of production studies of the CW geometric parameters was carried out according to the following principle:

– the actual array of measured points was compared with the theoretical surface of the wing (master geometry);

– control of the installation of the CW cross-sections in the plane of the ribs and the installation angles of the initial profiles (IP) of the wing was carried out along the centers of the joint bolt holes (in the X and Y coordinate system).

To determine the angles of installation of cross-sections, points lying on the CW surface the area of intersection of spars with ribs were used. Based on the results of production studies, the difference between the angles of the theoretical section (master geometry) and the actually measured (manufactured) section was calculated. At the same time, a one conditional theoretical chord of the CW box section was taken as a basis. The segment connecting the midpoints of the cross-section heights in the plane of the first and second spars was taken as a conditional theoretical chord. The absolute value of the difference in the angle of deviation (Δ, min) of the actual chord of the CW box section from the theoretical chord is the deviation of the installation angle (Fig. 9).

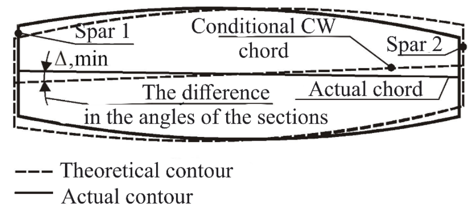

Fig. 9. Scheme for determining the difference in the installation angles of the theoretical and actual CW box sections

According to a similar scheme, the installation angles of the jig locators and the CW output sections were determined.

3. Results and Discussion

3.1. Stages of studying the geometric parameters of the cantilever wing. Due to the long duration of the manufacturing process of the cantilever wing, inspection studies of geometric parameters were carried out during three stages.

At the first stage, inspection (scanning with the help of a laser tracker) of the jig for the CW assembly was carried out, the actual angles of installation of locators and the angles of installation of the initial profiles (IP) of the wing, which this jig is capable of providing, were calculated. The results of the calculations are presented in Fig. 9–11.

At the second stage of production research, the inspection of the actual parameters of the CW geometry after removing the CW from the jig and analyzing them for compliance with the original theoretical data (geometry master) was carried out.

The inspection was carried out on the off-jig work (OW) stand in an unloaded state.

According to the results of the real data, the installation angles of the CW cross-sections along the ribs and the deviation parameters of the contour of the cross-section in the area of the spars were calculated.

The listed geometric parameters of scanning and calculations are shown in the graphs of Fig. 12–18.

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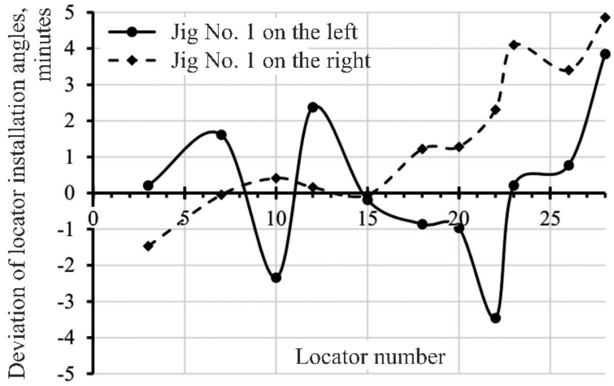

Fig. 10. Deviation of the installation angles of the locators of the CW jig set

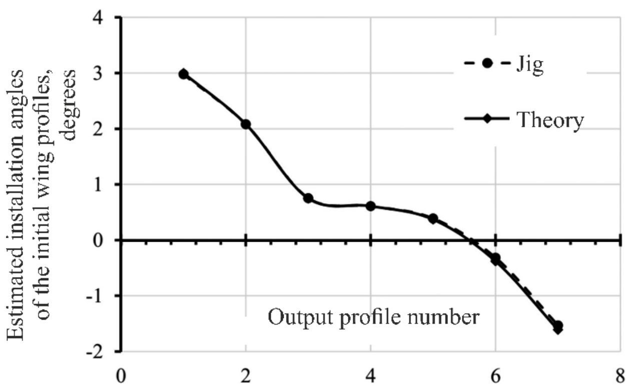

Fig. 11. Estimated installation angles of the initial wing profiles, which are able to provide the CW jig

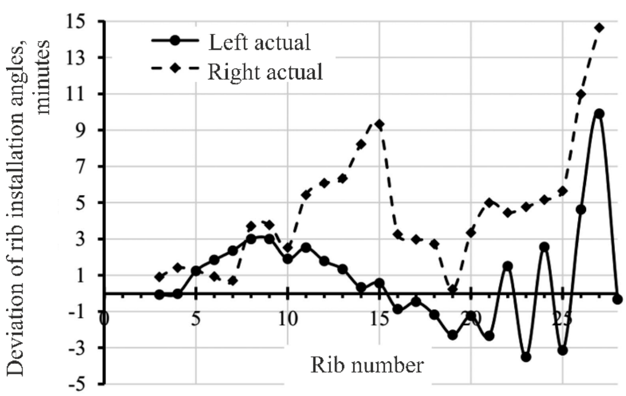

Fig. 12. Deviation of the installation angles of the sections of the left and right CW along the ribs

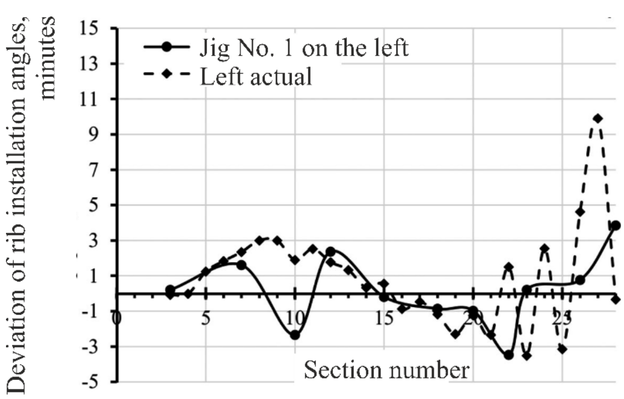

Fig. 13. Deviation of the installation angles of the sections of the left CW and the left jig

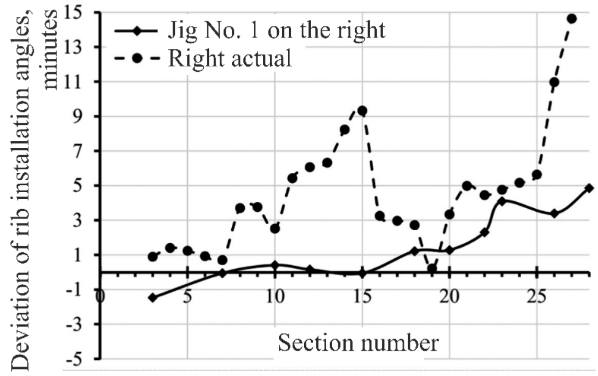

Fig. 14. Deviation of the installation angles of the sections of the right CW and the right jig

Based on the results of the data obtained at the second stage, the following conclusions can be drawn:

– on the left CW there is a sharp jump in the deviations of the angles of setting the sections (in the area of rib 22), the actual angles do not correspond to the predicted values obtained after the analysis of the jig, these values are more significant than the deviation of the jig;

– there is no jump in the deviations and angles of the cross-sections on the right CW, they are closer to those predicted on the basis of the jig geometry (Fig. 14), in contrast to the left CW, where there is a jump in angles, in the area of ribs from 22 to 28 (Fig. 13);

– the thickness of the profile in the zone of CW contact with the center plane (on the left and right cantilevers) exceeds the theoretical MG value by 3 mm (Fig. 15–18).

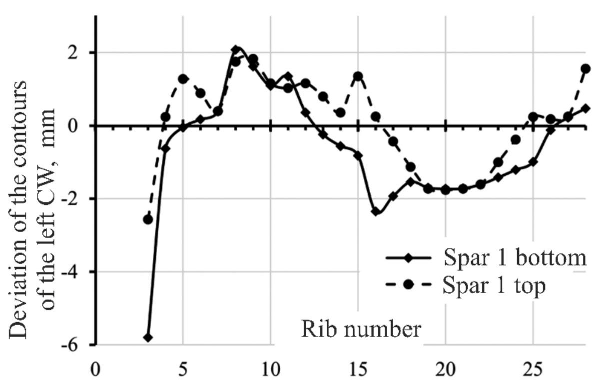

Fig. 15. Deviation of the contour of the left CW in the area of spar 1

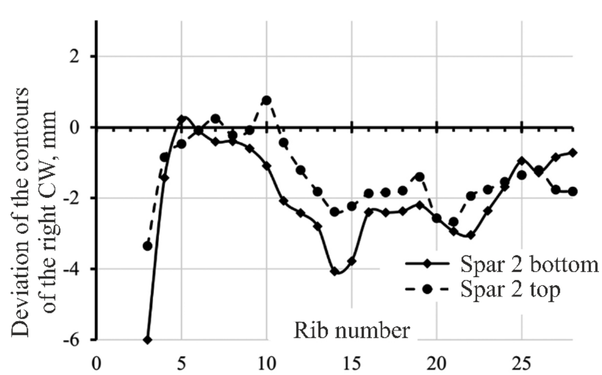

Fig. 16. Deviation of the contour of the left CW in the area of spar 2

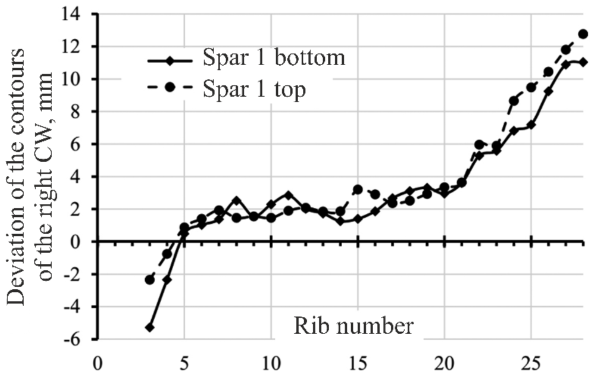

Fig. 17. Deviation of the contour of the right CW in the area of spar 1

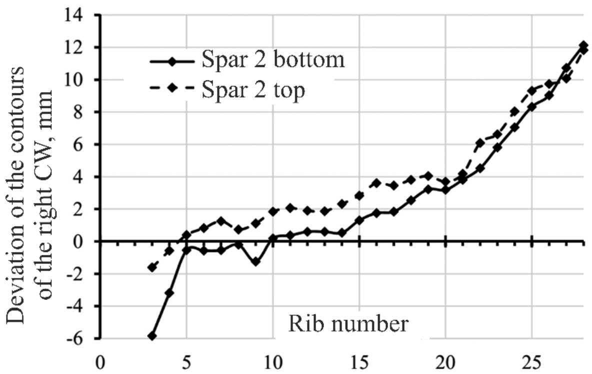

Fig. 18. Deviation of the contour of the right CW in the area of spar 2

The next stage of control of the CW geometric parameters was installation on the aircraft (without engines, mechanization and other equipment). When scanning with a tracker, the CW was in a free position (without supports).

The results of the analysis of the obtained data are presented in the graphs of Fig. 19–21.

The following conclusions can be drawn based on the results of CW scanning installed on the aircraft:

– the deviations of the installation angles of the CPW cross-sections practically correspond to the deviations that were detected on the stand of off-jig works (Fig. 19–21);

– on the left CW, there is a uniform increase in the angles of installation of sections, in one direction for an average of 2–5 minutes, i. e., a slight twisting of the cantilevers upwards is observed.

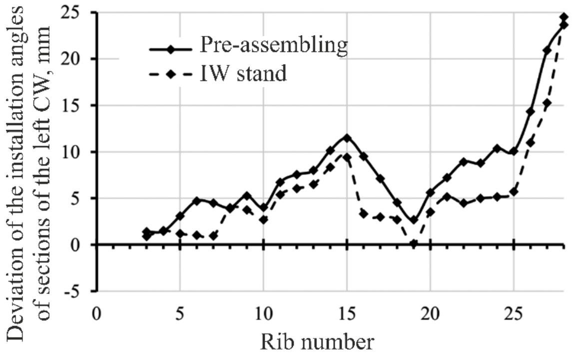

Fig. 19. Deviation of the installation angles of the sections of the left CW during measurements on the off-jig works and during pre-assembling

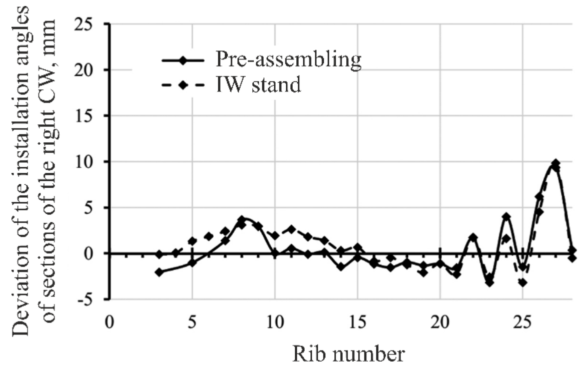

Fig. 20. Deviation of the installation angles of the cross-sections of the right CW during measurements on the stand of off-jig works and during pre-assembling

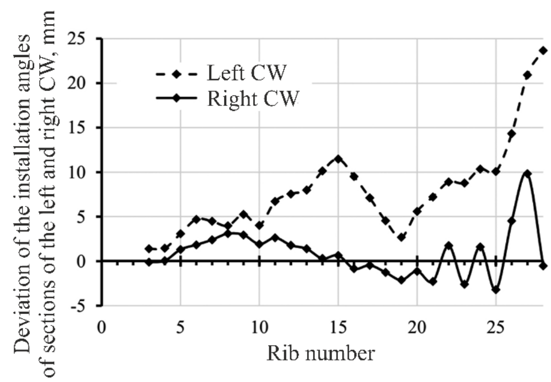

Fig. 21. Deviation of the installation angles of the sections of the left and right CW during pre-assembling

Conclusions regarding the research of the CW geometric parameters:

– after removal from the jig, the CW has deviations that exceed the similar deviations of the jig;

– the left CW has larger deviations of the angles of setting sections than the right (in the area of ribs 22–28);

– hanging the CW on the plane slightly increases the twist by an average of 2–5 minutes;

– the obtained data indicate that the CW deformation occurs in the zone of the 2nd spar behind rib 22 after removal from the jig.

3.2. Discussion. *Practical meaning.* The obtained results show that this method of no-loft linking can be used in the modern production of aircraft. Because the total dimension error during co-ordination is minimized at the mounting stage due to the absence of rigid form carriers. The technology does not add complications to the procedure of assembling a ready-made aircraft, but, on the contrary, simplifies it and reduces the overall time. And the portability of modern laser optical systems allows to deploy and adjust the operation of the devices directly near the object.

Limitations of the study. For successful practical application in production, it is suggested to use the described method on aircraft of the AN series: An-158, An-178, An-132, since the determination of the permissible range of deviations of geometric parameters was performed on one of the typical models.

The influence of martial law conditions. Due to the state of war on the territory of Ukraine, the question arose of the need to provide the Armed Forces of Ukraine with various types of equipment. Aviation is strategically important for controlling the situation in the sky. The proposed no-loft linking shape and dimension method using laser optical systems for the mounting of aircraft aggregates will speed up their production. And this will reduce the waiting time when ordering aviation equipment from the factory to the manufacturer.

Prospects for further research. In the future, it is planned to conduct a study of the geometric parameters when installing each of the subassemblies on the aircraft and determine the range of possible deviations of the shape and geometry from those specified in the documentation.

4. Conclusions

In the course of the study, it was shown that the application of the method of no-loft linking shape and dimension method using laser optical systems in aircraft production allows to significantly reduce the labor intensity and cycle of mounting work up to 10 times by eliminating the need for designing, manufacturing and operational support of carriers of rigid shapes and dimensions.

The use of laser measuring tools in aircraft construction makes it possible to significantly reduce the metal consumption of technological equipment, compared to traditional mounting methods that use rigid carriers of shapes and dimensions.

The use of laser measuring systems during the mounting of equipment allows to reduce to a minimum the impact on the accuracy of the low rigidity of the frames, the deformation of the equipment due to the mass of the parts of the assembled aggregates, and temperature deformations. And, thus, to ensure an achievable mounting error of ±0.1 mm, which meets the requirements of modern aviation equipment.

The use of laser optical systems allows to enter the plane's coordinate system without prior leveling, and thus to carry out the mounting and inspection of the installation on the fuselage of the wing, fin, stabilizer, engines and landing gear. The system is deployed directly next to the aircraft. Inspection over the mounting of aggregates is carried out at control points with reference to the product coordinate system. With the help of adjustment devices, the mounter just needs to connect the control points with their visualization in space, take an inspection measurement and print it out on the monitor.

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.

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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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