The issues of improving technical facilities are always important. Progressive in this regard are computer information technologies. Complex automation of production shortens the time of creating new products, significantly increases the quality, and reduces the cost. An important task is to combine automated design and manufacturing of products on the basis of geometric modeling. Technological processes of mechanical engineering, particularly in the aviation industry, are characterized by a large number of assembly operations, cutting, pressure cutting, etc., with a large number of possible options. Taking into account the existing requirements for increasing the accuracy, flexibility, productivity, and shortening the time of production preparation, it is necessary to apply new approaches in the field of computer information technologies, which determines the relevance of the outlined scientific issues.

1. Introduction

The main focus is the integration of Pro/Engineer systems and Microsoft Excel spreadsheets, and the study justifies the possibility of increasing the productivity of automated construction at the expense of this approach. The universality and flexibility of parametric methods of geometric modeling is confirmed by article [2], where the corresponding computer constructs of such widespread engineering products as screw cylindrical wire springs are presented. Work [3] shows the effectiveness of information technology data for automated reproduction of assembly units of machine building on an example of a mechanism with two kinematic pairs. The study extends the methods of parametric geometric modeling to the assembly of the unit. However, the general disadvantage of the above-mentioned works is that they do not analyze the integration of the design of technical objects, for example, with calculations of durability, processes of manufacturing, operation, etc.

Study [4] highlights the kinematic optimization of mechanical systems on the basis of dynamic computer simulation. Article [5] shows the effectiveness of using parametric geometric means for combining automated solid-state shape forming with calculations of durability and development of design documentation. Thus, we see that the progressive modern trend is to expand the scope of the practical application of parametric geometric modeling during the creation of various technical objects.

A certain improvement of the analyzed approach to computer geometric modeling is parametric structural shape formation, the main provisions of which are given in article
In the study, one parametric structural geometric model summarizes several parametric ones, which greatly increases the universality and performance of automated design. Work [7] describes some issues of the use of parametric structural shaping for the development of an aircraft, but the focus is on the stage of sketch design. In article [8], the emphasis is placed on efficient computer modeling of a large nomenclature of unified group of parts, but integration problems with the technology of their production, calculations of durability, etc. are not considered. In article [9], it is shown that further development of parametric structural geometric modeling is a computer variant dynamic formation.

Thus, the analysis of the published data shows that the development of new approaches, methods, techniques and algorithms of the integrated computer variant dynamic formation of technical objects and mechanical engineering processes on the basis of structural and parametric geometric modeling can be regarded as promising in both theoretical and practical terms.

3. The aim and objectives of the study

The aim of the study is to develop, on the basis of structural and parametric geometric modeling, a method of computer variant dynamic formation of technical objects with illustration guidance on the example of an aircraft wing.

To achieve the aim, the following tasks should be solved:

– to offer a mathematical apparatus of the dynamic formation of technical objects;

– to perform an automated variant construction of the surface of the aircraft wing;

– to carry out dynamic computer structural and parametric geometric modeling of the longeron of the central part (centripetal) of the aircraft wing.

4. The mathematical apparatus of dynamic shaping of technical objects

For the computer variant dynamic formation of technical objects, geometrical figures will be used according to their classification by the dimension

\[ F = \{ F_i \}_{i=1}^{n}, \]

where \( F_i \) is points, \( F_i \) is lines, \( F_i \) is surfaces, and \( F_i \) is bodies.

The geometric parameters will be presented as a tuple

\[ P = \{ P_i \}_{i=1}^{n}, \]

where \( P_i \), \( P_j \), and \( P_k \) are position, size and shape parameters.

According to expression (2), possible dynamic geometric modifications are described by the set

\[ M = \{ M_i \}_{i=1}^{n}, \]

where \( M_i \) is the modification of the position (movement), \( M_i \) is the modification of dimensions (similarity), and \( M_i \) is the modification of the form (deformation).

On the basis of relations (1)–(3), the investigated types of dynamic modifications of figures are determined by the tuple

\[ MF = \{ MF_i \}_{i=1}^{n}, \]

where

\[ MF_i = F_i \times M_i, \]

The object under consideration is a certain combinatorial configuration of the elements of set (1), and its modifications are obtained from the elements of tuple (3). It is necessary to take into account the further details of these components, for example in the form

\[ F_i = \{ F_{i1} \}_{1=1}^{n} = (L_{1}), \]

where \( F_{i1} \) is (first-order lines) \( (L_1) \), \( F_{i2} \) is (second-order lines) \( (L_2) \), \( F_{i3} \) is (other lines) \( (L_3) \);

\[ F_i = \{ F_{i1} \}_{1=1}^{n} = (S_{1}), \]

where \( F_{i1} \) is (transfer surfaces) \( (S_1) \), \( F_{i2} \) is (rotation surfaces) \( (S_2) \), and \( F_{i3} \) is (other surfaces) \( (S_3) \);

\[ F_i = \{ F_{i1} \}_{1=1}^{n} = (B_{1}), \]

where \( F_{i1} \) is (multifaceted bodies) \( (B_1) \), \( F_{i2} \) is (rotation bodies) \( (B_2) \), and \( F_{i3} \) is (other bodies) \( (B_3) \);

\[ M_i = \{ M_{i1} \}_{1=1}^{n} = (m_{1}), \]

where \( M_{i1} \) is (parallel transfer) \( m_1 \), \( M_{i2} \) is (rotation) \( m_2 \), and \( M_{i3} \) is (symmetry) \( m_3 \);

\[ M_i = m_{1}, \quad M_i = m_{2}, \quad M_i = m_{3}, \]

where \( m_{1} \) is (proportional scaling), and \( m_{3} \) is (disproportionate scaling).

On the basis of parametric structural shaping, an arbitrary simulated geometric object \( O \) is represented by an ordered set of elements:

\[ O = (a_{1}), \]

The possible types of \( a \) are reproduced by tuples of variants

\[ a_o = (a_{1}), \]

and vectors of parameters

\[ P_o = (P_{1}), \]

where \( N_{P_o} \) is the number of parameters of a \( j \)-th variant of an \( i \)-th element.

The structural correlation between the varieties of the \( n \)-th and the \( m \)-th components of the object \( O \) is determined by the adjacency matrices (Fig. 1, a).

\[ C_{nm} = \{ c_{ns}, c_{ms} \}, \quad n \in N; \quad m \in N; \quad n \neq m; \quad r \in \{1, \ldots, N_o\}; \quad s \in \{1, \ldots, N_o\}, \]

where \( c_{ns} \) and \( c_{ns} \) are not any possible interaction of the options \( a_o \) and \( a_m \); otherwise, \( c_{ns} = 0 \).

As a result of using dependencies (10)–(13), the model object \( O \) is provided by a set of design options

\[ O = (a_{1}), \]

where

\[ MF_i = F_i \times M_i, \]

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\[ MF_i = F_i \times M_i. \]
For a variant dynamic reproduction of technical objects and processes for their manufacturing, the specific composition of sets (1)–(14) is determined by the existing design conditions, which are illustrated later by specific examples of structural and parametric geometric modeling of the aircraft wing.

5. The results of variant dynamical geometric modeling of the aircraft wing

The following is a variant modeling of the wing surface, which largely determines such characteristics of the aircraft as aerodynamic, strength, weight, technological, etc., as well as computer dynamic structural and parametric shaping of the centreplane longeron.

The indicated information is important in the applied scientific plan because using modern computer information technologies provides an opportunity to increase the efficiency of conducting complex (multicriteria) optimization of the aircraft. This assertion is based on the fact that the tasks of aerodynamics, strength, layout, construction, technology of production and operation, etc. are not only closely related, but they also significantly affect one another. For example, tolerances in terms of the strength of the limit on the variation of the height of the longeron ends is determined by the shape and dimensions of the cross-sectional wings, selected in accordance with the required aerodynamic characteristics, and the latter, in turn, depend to a large extent on the stiffness of the structure of the bearing surface. Also, the complication of the shape of the wing leads to the improvement of its aerodynamics but worsens the manufacturing process. These and other features determine the iterative variant nature of the design of a modern aircraft. Among many other models (aerodynamics, strength, layout, weights, technological, operational, etc.), geometric models have a special place, which is related to the role of the model of the shape and size of the simulated technical object. As a result, the main requirements for computer geometric models ensure not only high accuracy of shaping but also flexible and productive construction of various design variants of products with a dynamic reflection of the included processes of their manufacture and operation, that is, for the entire life cycle.

The following specific examples confirm the validity of the above general methodology of the computer variant dynamic formation of technical objects on the basis of structural and parametric geometric modeling.

5.1. The variant construction of the surface of the aircraft wing

Let the surface as the output have an aerodynamic profile, represented in a rectangular coordinate system Ox'y' by a set of points

\[ r = \left( x_i, y_u, y_l \right)^\top, \]  

(15)

where \( x_i \) is the abscissa of the points, \( y_u \) and \( y_l \) are, respectively, the ordinates of the upper and lower parts of the profile, and \( n \) is the number of points in each part.

Usually, the abscissas \( x_i \) as well as the ordinates \( y_u \) and \( y_l \) are expressed as a percentage of the length of the chord \( b \), that is, the segment of the line that combines the two most distant profile points and divides it into the upper and lower parts.
According to expression (3), the possible modifications of profile (15) are the position change as well as the proportional and disproportionate types of scaling. The latter is presented later on the example of the dynamic variation of the profile thickness and concavity.

The profile height and the average line are calculated as

$$h = y_m - y_t, \quad y_m = 0.5(y_u + y_i).$$

(16)

The longest segment $h$ is called the thickness $c$ of the profile, and the maximum distance from the points $y_m$ to the chord is the concavity $f$ of the profile $f$ (Fig. 2).

![Fig. 2. Modifications of the shape of the discrete aerodynamic profile: a shows the output profile NACA-0009 ($f=0\%$ and $c=9\%$); b means $f=2\%$ and $c=9\%$; c shows $f=2\%$ and $c=13.5\%$](image)

To modify the profile with the coefficient of concavity $k_i$, and the thickness factor $k_c$,

$$k_i = f' / f, \quad k_c = c' / c,$$

(17)

where $f'$ and $c'$ are a new concavity and a new thickness; the starting points of (15) are transformed as follows:

$$y'_u = y_u k_i + 0.5h k_c = 0.5(y_u(k_i + k_c) + y_i (k_i - k_c)),$$

$$y'_i = y_i k_i - 0.5h k_c = 0.5(y_i(k_i - k_c) + y_i(k_i + k_c)).$$

(18)

where $y'_u$ and $y'_i$ are the modified ordinates of the points of the upper and lower parts of the aerodynamic profile.

Under the conditions of using the initial symmetric profile, the required initial concavity $f$ is obtained by multiplying the ordinates of the points of the upper and lower parts, respectively, by the coefficients

$$k_u = (f + 0.5c) / y_u, \quad k_i = (f - 0.5c) / y_i$$

(19)

where $y_{max}$ and $y_{min}$ are the maximum and minimum ordinates of the initial profile.

The picture of Fig. 2 illustrates the practical application of formulae (15)–(19).

In the case of processing the lines, for example, of the $F_1$ shape in accordance with expression (5), the possible dynamic transformations are shown in Fig. 3, where the studied aerodynamic profile is presented as a composite line of arcs of the curves of the second order in the vector parametric form

$$r_i(u) = \frac{(1-u)r_{0i} + w_i (2u(1-u)r_{0i} + ur_i)}{(1-u) + w_i (2u - u) + ur_i},$$

(20)

where $i \in \{t, b\}; j \in \{1, 2\}$;

$$r_{0i} = (x_i, y_i), \quad r_i = (x_{i1}, y_{i1}), \quad r_j = (x_{i2}, y_{i2})$$

are the radius vectors of the vertices of characteristic triangles in the rectangular coordinate system $Oxyz$. $w_1, w_3 \geq 0$ means the weights of vertices $r_i$ and $w_2 \in [0, 1]$ is the parameter.

In expression (20), $t$ and $b$ denote the top and bottom parts of the profile, and the index $j$ means the maximum and minimum ordinals of their arcs connected at the point with the maximum thickness abscissa. Fig. 3 shows modifications, where we use weight ratios of 0.5 and 1, respectively, for the nose and tail sections of the profile.

![Fig. 3. Modifications of the aerodynamic profile of curves of the second order: a is the output profile ($f=0\%$ and $c=10\%$); b means $f=1\%$ and $c=10\%$; c means $f=1.5\%$ and $c=12\%$ ($k_i=1.5$; $k_c=1.2$)](image)

After defining the shape of the aerodynamic profile, its proportional scaling to the desired size and setting in the proper position is carried out. Fig. 4 illustrates the linear surface of an arrowhead defined in a rectangular coordinate system $Oxyz$: the basic geometric parameters are the root $b_y$ and final $b_z$ chords, as well as the $L$ width and the arrow-shaped angle $\chi$. The derivative characteristics are represented by the area $S=b_y b_z L$, where $b_y=0.5(b_y+b_z)$ is the average chord, the elongation $\lambda=L/b_y L^2/S$, and the narrowing $\eta=b_y/b_z$.

![Fig. 4. The plan view of the aircraft wing](image)

The parametric equation of the wing surface is the following:

$$r_i(u,v)=(1-v)r_i(u)+vr_i(u),$$

(21)

where $i \in \{t, b\}; j \in \{1, 2\}; u \in [0, 1]$ and $v \in [0, 1]$ are the parameters.
The use of the indices $i$ and $j$ in formula (21) is similar to expression (20), and the upper indices $\theta$ and $k$ are the root and final aerodynamic profiles.

5.2. The dynamic computer structural and parametric geometric modeling of the centerplane longeron of the aircraft wing

The parametric structural model of the longeron presented in [10] makes it possible to obtain the necessary design variants, but it does not allow reproducing in time technological operations of installing parts, drilling holes, riveting, etc. Let us consider some techniques for improving this model.

The composition of the projected longitudinal $LN$ is represented by the set

$$ LN = \{LN\}_i^j, $$

where $LN_i^j(W)$ is the wall; $LN_i^j(B_i, B_j)$ means the upper and lower belts; $LN_i^j = (St_i)^N_{di}$ denotes stilts ($St$); and $LN_i^j = (Rv_i)^N_{di}$ denotes rivets ($Rv$).

Let the manufacturing of node (22) determine the tuple of technological operations

$$ T = \{T\}_i^j, $$

where $T_i^j =$ \{Install $W_i$, $B_i$, $B_j$ \}; $T_i^j =$ \{Drill, rivet $B_i$, $B_j$ \}; $T_i^j =$ \{Install $St_j$, $j = 1, \ldots, N_{IN}$ \}; $T_i^j =$ \{Drill, rivet $St_j$, $j = 1, \ldots, N_{IN}$ \}; $T_i^j =$ \{Control the assembled $LN$ \}.

According to the general approach described, the figures of (22) are the bodies, and the technological operations of (25) are geometrically reduced to the change in the parameters of the position and the shape of these objects.

Fig. 5 (using the front and left views) shows the result of the $T_i^j$ operation.

The parameters of the wall $W$ as a rectangular parallelepiped are length, height, and thickness. For the $T$-shaped belts $B_i$ and $B_j$, the parameters are the dimensions of the cross sections and the length. The operation of installing these parts consists in moving them to the necessary position of the proper base, which for the bodies can be carried out by the conjugation of face surfaces, edges, vertices, etc.

The operation $T_5$ is illustrated in Fig. 6, where the belts are attached to the wall of the longeron through drilling of the required holes and subsequent riveting.

For a dynamic simulation of the drilling of cylindrical holes, it is recommended to use a computer solid-state drill model and its geometric model presented in the Cartesian coordinate system $Oxyz$ as a combination of a cone

$$ r(x, y, z) = \frac{D}{2} \left( (1 - w)^2 \cos(2\pi u), (1 - w)^2 \sin(2\pi u), wH \right) $$

and a straight circular cylinder

$$ r(x, y, z) = \frac{D}{2} \left( v \cos(2\pi u), v \sin(2\pi u), wH \right), $$

where $D$ is the base diameter; $H$ is the height; $w \in [0, 1]$, $v \in [0, 1]$, and $w \in [0, 1]$ are the parameters.

Fig. 6. The technological operation $T_5$ of drilling and riveting the belts $B_i$ and $B_j$; $a$ is the general view; $b$ is the beginning and completion of drilling a hole; $c$ is the beginning and completion of riveting.

Expressions (24), (25) determine the part of the space occupied by the drill at its rotation. During the working process, the drill moves and cuts into the part. From a geometric point of view, this means a Boolean operation of subtracting the proper rolling volume of the drill from the part.

For the computer dynamic constructions of closing heads of rivets, we will use a geometric model of settling a direct circular cylinder, which is shown in Fig. 7.

Fig. 7. A model of settling a cylinder

The output cylinder has the base radius $R$ and the height $H$. For the settled body, the relative compression is

$$ e = \frac{(H - H')}{H}, $$

where $H'$ is the reduced height, and $R_{\text{min}}$ and $R_{\text{max}}$ are the increased radii of the bases in the contact planes and the median horizontal plane of symmetry.

The lower and upper parts of the lateral surface of the settled body, which are symmetrical in relation to the median horizontal plane, are formed in the rectangular coordinate system $Oxyz$ by rotating around the axis $z$ of the arcs of the second order curves:
where i = (b, t) are the indices of the bottom and top parts;

\[ r_{ib} = (0, R'_{max}, 0), \quad r_{it} = (0, R'_{max}, 0), \quad r_{tb} = (0, R'_{max}, H'/2), \]

\[ r_{tb} = (0, R'_{max}, H'/2), \quad r_{t} = (0, R'_{max}, H'), \quad r_{b} = (0, R'_{max}, H') \]

are the radius vectors of the vertices of the characteristic triangles; \( \alpha \geq 0 \) is the weight ratio of the peaks \( r_{i} \); and \( \alpha \in [0, 1] \) is the parameter.

During plastic deformation of the body, its volume is considered to be constant and is calculated as

\[ V = 2 \pi \int_{0}^{1} u^{2/3} \left( u^{1/2} + \int_{0}^{u} w(t) \right) dz = 2 \pi \int_{0}^{1} u^{1/2} \cdot \frac{1}{2} \left( 1 - u + w(t) \right) H' \]

The automated variant construction of the aircraft wing surface and the dynamic solid-state modeling of the centerplane longeron are of practical importance. The results have confirmed the reliability of the proposed method of computer-based variant dynamic formation of technical objects on the basis of the parametric structural approach. This applies to the classification of applied geometric figures and their modifications, a combination of stages of sketch, technical and working designs, and the reproduction of certain technological processes of mechanical engineering.

Due to the controversial requirements of aerodynamics, strength, production and operation of the variation of the shape, size and position of the aerodynamic profiles of the projected wing, it is implemented by flexible means. The presented techniques of computer construction are aimed at ensuring the successful implementation of the appropriate multicriteria optimization. Thus, the presence of the possibility of parallel transfer of the final profile \( r \) in the model (Fig. 4) along the \( z \) axis determines the required \( L \) width of the wing; along the \( x \) axis, the angle \( \gamma \) is sagittal, and along the \( y \)-axis, the angle \( V \) is transverse. The profile rotation around the parallel \( z \) axis of the straight line provides a bearing for the aerofoil. It is also important to emphasize the variant nature of the created model of the wing longeron. Each element has its own geometric parameters of shape, size, and position. For example, the cross-section of the stilts can be not only angular (Fig. 8) but also T-shaped, and the stilts have certain dimensions and necessary quantity to be located properly.

Consequently, the fundamentally new features of the proposed dynamic parametric structural geometric models are the presence of their parameters related to the displacement and deformation of the constituent elements.

It is known that the development of complex technical objects, in particular in the aviation industry, has an iterative variant nature. Thus, during the technical task, the main characteristics of the product are determined, the possibility and expediency of its manufacturing are substantiated. The technical proposal contains the specified technical and economic characteristics, the draft design (the fundamental engineering solutions that give a general idea of the structure and operation of the product), and the technical design (the final technical solutions that give a complete picture of the product). In the aviation industry, at the stages of the sketch and technical projecting, various layouts of the technical object and its components are created, which is now often performed in a computerized form, and manufactured. In the course of the working design, the documentation for producing prototypes is first drawn up, and then, after proper correction on the basis of tests, mass production is launched.

In all of the above-mentioned stages of creating technical objects, geometric models are used, which are gradually complicated and refined in accordance with the stages of the lifecycle of mechanically engineered products.

The techniques and algorithms of parametric structural geometric modeling have been implemented at the Antonov Aviation Scientific and Technical Complex during the design of the AN-148 aircraft, the production of the trolley...
bus K12 at the State Enterprise Kyiv Aviation Plant Aviant, while performing design and development works for manufacturing technological equipment at the Kharkiv Aviation Manufacturing Enterprise, as well as while developing a system for automation of processes for the formation of a three-dimensional model of a vessel’s hull at the Open Joint Stock Company “Research Institute of Automated Systems and Computer Science in Shipbuilding”, and at other leading enterprises of Ukraine.

A promising direction of the modern development of parametric structural geometric modeling in the scientific and practical aspects consists in its further improvement by devising new methods, techniques and algorithms of dynamic shaping, which will significantly increase the accuracy and realism of the computer models. Some of the aforementioned issues have been elaborated in this paper by the proposed method of computer-based variant dynamic shape-forming of technical objects, which is illustrated by the example of the wing of an aircraft.

7. Conclusions

1. The scientific theoretical novelty of the obtained results consists in the development of a mathematical apparatus for the dynamic formation of technical objects, which is aimed at improving and further developing of computerized structural and parametric geometric models by appropriate integration with their available mathematical support.

2. The practical value of the obtained results consists in creating a method for the use of parametric structural geometric modeling for computer variant dynamic formation, which allows a flexible combination of the processes of designing and manufacturing technical objects.

3. The obtained practical results have confirmed that the proposed techniques of automated construction provide integrated processing of technological processes used in the manufacture of aircraft products.

4. The presented materials can be applied to various products of mechanical engineering and other industries.

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