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DESIGNING THE WORKING SURFACES OF ROTARY PLANETARY MECHANISMS

Purpose. To design a method for smoothing the working surfaces of stator and rotor with the use of computer simulation to eliminate the impact of the rotor on the stator when they interact.

Methodology. Special and general methods of research have been used: interpolation of the point series – to determine the contour nodes of the rotor and the stator of the rotary-planetary machine; formation of B-splines – to construct a point series whose coordinates are structurally determined; technology of automated formation of curves in CAD-system SolidWorks – for modelling of functional surfaces of a planetary-rotary compressor.

Findings. Algorithms for formation of the contours representing curves defined analytically or constructively with a given accuracy have been developed. The obtained contours are used in the CAD system as linear elements of the surface model. The developed method has been tested in the simulation of functional surfaces of a planetary-rotary compressor. Optimization of the body shape and rotor profiles in order to increase the productivity of the rotary-planetary machine has been carried out.

Originality. The developed algorithms make it possible to determine the original point series belonging to any curve and provide a given interpolation accuracy when forming a B-spline contour or second-order curve arcs. Computer models of the body surfaces of the rotor are formed on the basis of the gear ratio of the planetary-rotary mechanism and the rotor dimensions. In order to increase the performance of the compressor, the working surfaces of the rotor have been optimized. The maximum volume of the working chamber was increased by increasing the radius of the moving gear of the planetary-rotary mechanism. In order to prevent the rotor from jamming during compressor operation, the rotor contour was changed.

Practical value. The method for modelling the surfaces of complex shape in CAD-system has been developed on the basis of creating contours which with given accuracy represent lines from the surface determinant. This method makes it possible to form computer models of complex surfaces on the basis of a framework consisting of curves absent in CAD libraries.

Keywords: *rotary planetary mechanism; computer model, epitrochoid contour, rotor, stator, gear ratio*

Introduction. At present, the production of rotary and rotary planetary machines and mechanisms is widespread due to their simple design and good weight and dimensional indicators. This class of machines comprises a large number of design schemes, which differ from each other, both in movement kinematics of their working organs and in rotor profile surfaces design. This diversity is reasoned by the attempts to address the technological deficiencies inherent in almost all known design schemes of rotary machines and to improve their performance and energy efficiency [1].

Further development of rotary-planetary machines is to a great extent determined by the degree of geometric perfection of their working surfaces. In practice, it often demands the application of modern approaches to the contours and surfaces, which limit their working capacities, affect their parameters and thus determine the quality of rotary-planetary machines.

However, the degree of geometric perfection of the contours and working surfaces of rotary-planetary machines mentioned above is not fully ensured by existing geometric design methods. Therefore, solving the problems of geometric modelling, the construction of new geometric models of working surfaces of rotary-planetary machines in particular, is a current challenge.

The advance of information technology and development of new computer software provides the user with massive opportunities to visualize the results of geometric modelling of the working surfaces on the screen, which raises the solution of geometric problems to a qualitatively new level. In the case of RPM, this allows one move from consideration of individual tasks of profiling their elements to geometric modelling (construction of geometric models) of the whole working surface, depending on the ratio of the radii of the dividing circles of the gear transmission of the planetary mechanism, that is, to implement a system approach to the creation of rotary-planetary machines of various design. The use of computer technologies provides a comprehensive solution of the issue of increasing their efficiency.

Application of modern computer technology in geometric modelling and optimization of the parameters of working surfaces of rotary-planetary machines ultimately contributes to the creation of appropriate systems of computer-aided design, which not only automates the work of designers and frees them from routine work, but also creates conditions for effective search of design methods and finding the efficient solutions.

Literature review. The underlying problem in operating the rotary and planetary mechanisms is the impact of the rotor on the stator through their interaction. It is one of the stability and safety issues of rotational machinery. The friction type becomes decisive for predicting the rotary system's reactions [2].

Studies on the dynamic properties of rotor friction show that the friction caused by sudden loaded impact will always exist, and the friction induces the quasiperiodic movement of the rotor system [3].

Experimental and numerical research results demonstrate the predictive capabilities of the impact model between the rotor and the stator. The impact friction effect is a common phenomenon that occurs in industrial application of rotational mechanisms [4].

The self-induced vortex of reverse dry friction caused by the rotor/stator system interaction is the most destructive result of their friction [5, 6].

The rotor friction model with smoothing function proposed in [7, 8] can effectively determine the start of rotor friction and, at the same time, determine the properties of the rotor's instantaneous frequencies. In [9], the study on reliability and durability of bearings providing rotation of the rotor in rotor-planetary mechanism is presented. Based on the results of the studies, it was concluded that reliability of bearing units was sufficient. The authors of [10] conducted studies on friction forces that arise during the operation of the bearings of rotary-planetary mechanisms. The impact of friction on the operation of bearing units was analysed in detail. However, in this case, a reverse vortex effect is observed which makes the rotor unstable [11]. To ensure the stability of the rotary unit bearings in the rotary-planetary machine, it is necessary to ensure the quality of functional surfaces of both the rotor and the stator. This will eliminate the unplanned vibration of the bearings caused by the vortex effect.

One of the options for eliminating the impact of the rotor on the stator is to minimize the friction caused by their interaction by developing a method for smoothing their working surfaces using computer simulation/design.

Products that are bounded by surfaces of complex shape are produced on computer numerical control (CNC) machines.

The control program for CNC machine is created in automated mode with CAM software. The source data for CAM software is a three-dimensional computer model of the product created using CAD software (SolidWorks, AutoCAD, NX CAD, 3ds Max, etc.) [12]. Machining precision is determined by the accuracy of the 3D model design, the accuracy of the CAM cutter tool trajectory and the accuracy with which the machine performs the programmed operations.

The methodology of creating computer models of surfaces for different purpose mechanisms including modified cycloid reducer with epitrochoid tooth profile [13], sieves for fruit seeds calibration [14] and an oil pump [15] was developed. However, the presented methods for building computer models are based on the application of standard curves, which are available in the built-in libraries of CAD-systems. In this case, it is difficult to ensure that the working surfaces of the designed mechanisms are smooth at the junction of the segments of curves forming their contour. In [16,17], the construction of non-uniform rational B-spline surface models of free-form shapes was described based on frames comprising two curve families. The first family determines the movement of forming curves, which are the curves circumscribing the designed surface. This method of computer simulation of surfaces involves the use of models of abstract images with the least possible description. It should be noted that this is not sufficient to perform the task of ensuring the smooth operation of the stator/rotor system in the rotary-planetary mechanisms. In this connection, it is necessary to search for new, more effective methods, including methods of computer modelling of profiles of functional surfaces of rotary-planetary aggregates and machines. The curves of the second family specify the movement of the guiding curves. The forming and guiding curves represented analytically form the model frame based on the surface determinant. In [14] it includes B-spline, in [13,15] – second-order curves. While forming the frame elements for such surfaces with CAD tools, there is no need for further operations. However, such an approach to the formation of the framework of a surface consisting of curves of the second family cannot provide the required accuracy of the profile of the rotor or the stator of the rotary-planetary machine. In our opinion, it would be more efficient to use methods of geometric modelling of surfaces limited by smooth second-order curves to form the profile of the functional surfaces of the rotor and the stator of the designed rotary-planetary machine.

The mathematical justification for computer modelling of surfaces is presented in [13]. A point series and its geometric properties serve as the initial data for curve formation. The authors developed a methodology for designing computer models of surfaces specified by a point array with the use of automated design technology, as well as programs for CNC machining of the surfaces. It should be noted that the authors use the mathematical core of the CAD system software to form a curve, which is used in computer simulation of functional surfaces of machines and mechanisms. This makes it impossible to ensure the necessary smoothness of the profile of the designed elements of the rotary-planetary machine. This raises the question of the need to develop an entirely new algorithm for the design of rotor and the stator surfaces.

Subsets of points are isolated from the initial point array – these are the series of points forming the basis for linear elements of the surface frame. Then, based on a discrete linear frame represented by the families of forming and guiding curves, a computer model of the surface is designed.

The methodology of computer modelling of complex surfaces using combined sequential technology of electro-discharge cutting and electrochemical machining with a wire electrode is developed in [18]. Based on the analysis of the results of the experiment described in the work, it was concluded that the accuracy and quality of the designing and manufacturing of the components were improved. The analysis and results of the experimental test are given. It was proved that the use of methods of computer modelling allows achieving the necessary indicators of accuracy and quality of functional surfaces of parts produced according to this advanced technology. The authors developed the algorithm for creating smooth contours of the designed surfaces. It was verified that the use of computer modelling methods enables increasing the accuracy of designing the surface and the quality of the parts produced by CNC machining. However, this algorithm cannot be classified as a unified algorithm. The application of this algorithm is not possible for the formation and computer simulation of functional surfaces with a spiral surface. To eliminate this deficiency, it is necessary to improve the already existing algorithm of surface design of working organs of rotary-planetary machines or to develop a new algorithm and a new method of computer simulation, capable of providing the necessary accuracy and quality of the parts manufactured.

In [14,16] the surface determinant contains the curves that are not available in the CAD software library (cycloid and trochoid). To create the linear elements of the model, the following method was used: first, the coordinates of the points belonging to the curve were obtained analytically. Using CAD software, the obtained point series was formed and interpolated by a B-spline. With this method of curve formation, it is possible to ensure the accuracy of the working surface of the component being designed. However, to ensure reliability of the system rotor/stator without jamming, it is necessary to exclude dry friction on the surface of the rotor and stator. In this regard, there is a need to supplement the CAD libraries with algorithms for constructing new types of curves.

In papers [18,19] the matter of reverse engineering is addressed. The coordinates of points forming the model's linear elements are calculated by measuring the parameters of the existing products surfaces. The elements of the model are formed with CAD software by interpolation of the point series with a spline. But it should be noted that with this approach to designing the working surfaces of rotary-planetary machines it is difficult to ensure smoothness between parts of splines, which consist of the profile of the working surface of the rotor or stator at the points of their junction.

In articles [20, 21] a way of representing the flat and spatial trajectories of the cutter tool with the use of broken line or a compound curve was developed. The trajectory is created based on a series of points which belong to the surfaces of a three-dimensional computer model designed with the application of CAD software.

Depending on the amount of nodes of interpolation on the original curve, the accuracy of forming the contour representing the original curve is evaluated. In CAD software, manual mode can be applied to interpolating a series of points forming the curve. For example, while a B-spline is formed, the sequence of node points of the contour is indicated with a cursor on the screen. Contemporary CAD systems do not have any applications that allow creating the contours interpolating series of points in automated mode. Manual mode limits the amount of initial nodes, and therefore increases the error of the curves forming the contour. Assessment of the accuracy with which the curves formed with the use of CAD software represent theoretical trajectories is one of the challenges of surface modelling.

A method for calculating the maximum absolute error of representing the original curve is proposed in [20, 21]. The error of interpolation is obtained by determining the possible location of the curve with known geometrical properties. For plane curves, it is the growth direction of the curvature radii along the curve. For spatial curves, these properties are the run of the curve, the growth direction of the radii of curvature as well as the touching spheres radii. By measuring the distance between the points limiting the section, the possible location of the original curve is determined along with the contour interpolating the corresponding point series.

Mathematical tools allowed us to implement the method for determining the reliability of hydraulic motor [22, 23] by modelling the changes in technical condition of hydraulic motor rotors and to substantiate the geometrical parameters of the elements of distributive systems. The research enabled modelling of the connection of external and internal rotors, which can significantly improve the initial characteristics of planetary hydraulic machines and mechatronic systems of self-propelled vehicles [24]. Methods of mathematical analysis were also used in [25] to improve the working tools for combed heap separation of winter wheat.

So, solving the issue of using curves of every configuration in CAD systems specified both analytically and constructively is an important stage in the development of the technology for creating a control program for CNC machines.

Resulting from the analysis of the design and operating principle of rotary planetary machines and mechanisms, the main lack of reliability of their operation has been revealed. It is the jamming caused by a self-induced vortex of reverse dry friction produced by the rotor/stator system interaction. The present research looks into the ways to eliminate this deficiency by improving the geometry of rotor and stator working surfaces.

One of the ways of eliminating the impact of the rotor on the stator in the process of their interaction is to minimize the friction of the rotor on the starter by developing a method for smoothing their working surfaces using computer modelling of complex surfaces based on the frame, which consists of curves that are not presented in CAD software libraries.

In order to achieve the objective set, the following tasks must be accomplished:

1. Developing the algorithms for forming contours with given accuracy, representing curves, specified analytically or constructively, which are linear elements of the surface determinant.

2. Testing the developed methodology when forming functional surfaces of rotary planetary mechanisms.

Purpose of the article. The purpose of the paper is to offer a solution for the issue of jamming of the rotary-planetary machines caused by the self-induced vortex of the reverse dry friction produced by the interaction of the rotor/stator system. It is proposed to correct this deficiency by improving the geometry of the working surfaces of the rotor and the stator.

Methods. The design variant of the rotary planetary machine (RPM) with a two-arc epitrochoid is shown in Fig. 1. The main parts are the stator *1*, end discs *2*, body covers *9*, triangular rotor *17* with radial seal blades *16* and end seals *14*, the shaft *4* and balances *3*. The shaft is supported by two plain bearings *5* and plain bearing *7*, pressed into the rotor body. The gear *13* of the synchronizing apparatus is mounted on one of the ends of the rotor and is engaged to a fixed gear *8* mounted on the end cover. The channels of the stator *15* are used for connecting the distribution windows of the opposite disks (for two-way distribution). Distribution is performed by the rotor *17*. The suction and discharge distribution windows are connected to the fittings in the bosses of body cover *11* to connect the hydraulic machine to the mains.

The working surface profile of the machine is in the form of a two-arc epitrochoid with a module, and the rotor profile is in the form of Rello triangle ($z = 3$). The rotor, the output shaft of the rotary planetary mechanism rotates in one direction, the rotation speed of the shaft is three times the rotation speed of the rotor.

Consider the arrangement of the elements of the rotary planetary machine represented in Fig. 1 at minimum and maximum volumes of the working chamber (Fig. 2).

The rotary planetary machine generally consists of a body *1* and a rotor *2*. When the gear *3* connected to the rotor runs around the fixed gear *4* connected to the body, the rotor makes a planetary rotation inside the body. The vertices of the rotor are in constant contact with the inner surface of the body. The surfaces of the rotor and the body limit the three working chambers of the machine. When the rotor is rotated, the volume of the working chambers changes constantly. Fig. 2 shows

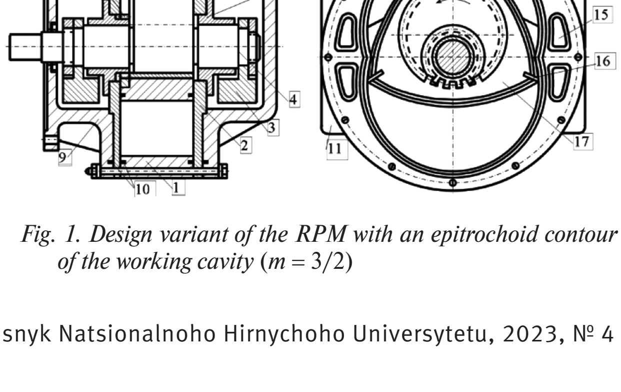
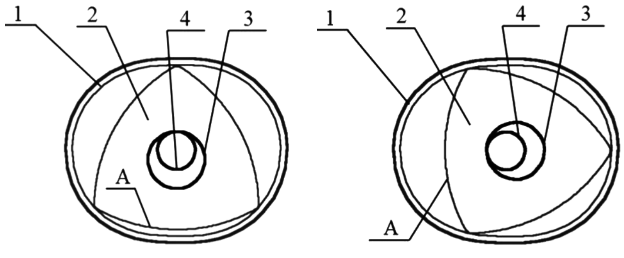


Fig. 1. Design variant of the RPM with an epitrochoid contour of the working cavity ($m = 3/2$)



a *b*

Fig. 2. Position of the working organs of the rotary planetary machine:

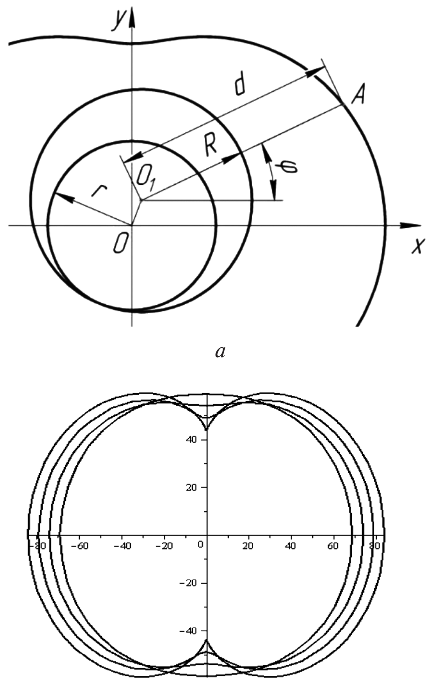
a — at minimum volume of the working chamber; b — at maximum volume of the working chamber

the rotor position where the working chamber volume is limited by A-side, maximum (Fig. 1, *a*) and minimum (Fig. 1, *b*). The performance of the rotary planetary machine is determined by the difference in the diameter of the gears of the rotary planetary mechanism (positions *3* and *4*) and the size of the rotor.

The working surface of the body is a cylindrical surface defined by the epitrochoid — a curve obtained by the movement of the rotor vertex (point *A*) rigidly connected to the distance d and angle φ with the circle of radius *R*. This chain rolls without sliding on the fixed circle of radius *r* (Fig. 3, *a*). The ratio between the radius of movable (*R*) and fixed (*r*) circles (gear ratio) is 3/2.

At a constant distance d, an increase in the radius of the chains causes the shape of the body to become more elongated, and the narrowest part of the body decreases (Fig. 3, *b*).

The result is an increase in the oscillation amplitude of the rotor and the difference between the maximum and minimum volume of the working chambers. The machine's performance increases. When the radii of the links increase, the moment comes when the profiles of the body and rotor intersect (the rotor is jammed in the body). For a rotor with a cross section



a

b

Fig. 3. Diagram of forming the working profile of the body of the RPM:

a — creating the epitrochoid family; b — epitrochoid family for different values of R at R/r = 3/2

in the form of a Rello triangle at *d* = 76 mm, the maximum possible radius of the separating chain of the moving gear is *R* = 29.72 mm.

Optimization of the rotor's profile was required to further increase in the volume of the working chambers.

The side of the optimized rotor profile is formed by a B-spline interpolating a point series, the coordinates of which are structurally determined. The position of the reference points is determined by a composite curve, the sections of which are formed as follows.

The position of the original rotor profile is fixed. The contour of the body is rigidly connected to the circle of radius r. This circle encircles the fixed circle *R*, and the body profile makes a planetary motion. This movement determines the part of the rotor falling within the limits of the different positions of the body contour (Fig. 4). Optimization of the rotor shape consists in removing the specified part.

The algorithm for determining the possible location of the curve is based on oscillation control (convexity-concavity change) in its sections [22]. For a convex curve with a single tangent position at each point, any section is located within the triangle, which shall be called the base. The base triangle (BT) is bounded by a chord connecting the points of the curve and touching the curve at these points.

Any contour interpolating a point series is preassigned on a convex curve on which no change in convexity-concavity occurs, and which is located inside the BT sequence with vertices at the node points of the contour. The longest height of BT can be considered the maximum absolute interpolation error.

In the case where the reference points of the contour are specified on an unknown curve, the points belonging to the contour are determined on the basis of its assumed properties. The growth direction of the radii of curvature along the curve is one of such properties. It is determined on the basis of adjacent chains passing through three consecutive points in the series. The growth directions of the radii of these chains along the curve and the radii of curvature coincide [22]. If the reference points of the contour cannot be determined on the basis of adjacent chains consisting of consecutive points of the selected series, there is a need to develop a more advanced algorithm for constructing a smooth contour with a sufficient degree of smoothness. The tangent line is defined as the mean position of two adjacent circles passing through a given point. In Fig. 2, the location adjacent to contour (*ti*) is defined within the sector bounded by lines '*ti* and *ti*'. '*ti* is the line which belongs to the nearest circle, passing through points *i* – 1, *i*, *i* + 1 (AC(*i* – 1, *i* + 1)) and *ti*' is the line nearest to '*ti* of those adjacent to AC(*i* – 2, *i* – 1, *i*) or AC(*i* + *i*)'.

Results. Based on the described algorithm, the technology of automated line formation in CAD software SolidWorks has been developed. In the first stage, the coordinates of points

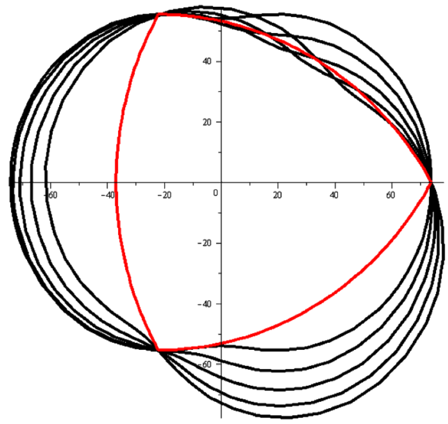


Fig. 4. Diagram of movement of the epitrochoid relative to rotor profile

belonging to the convex section of the modelled curve and the sequence of base triangles based on these curves were determined. The condition for the formation of the point series is that the maximum height of the base triangle does not exceed the allowed absolute error of curve formation in CAD system.

Maple environment was used to obtain the coordinates of the nodes of discretely presented curves. The coordinates of the obtained points in automatic mode were written in the form of text files.

In the second stage, a curve was formed with SolidWorks software. The program for forming curves was written in Delphi. When using the Application Program Interface, it was integrated with the CAD software – SolidWorks.

The text files containing the coordinates of the points calculated in Maple serve as the source data for the program. The program automatically creates a B-spline interpolating the original point series. On the basis of the acquired spline curve, a computer model of the surface is designed using the regular functions of SolidWorks.

The developed technology has been used for modelling the functional surfaces of a rotary planetary compressor.

The optimized body and rotor profiles have been formed for the moving chain radius R = 29.72 mm (the reference diameter of the moving gear of the RPM) and the distance d = = 76 mm (the distance from the centre of gravity of the rotor section to its apex).

The rotor side profile is formed on the basis of 32 nodes, the coordinates of which have been calculated according to the proposed method. The maximum interpolation error (δ_i) was $4.013 \cdot 10^{-4}$ mm (Table 1).

The selected parameters of the planetary rotor machine determined the body profile in the form of an epitrochoid defined by equations

$$\begin{cases} x = 10\cos\phi + 60 \cdot \cos\dfrac{\phi}{3} \\ y = 10\sin\phi + 60 \cdot \sin\dfrac{\phi}{3} \end{cases}.$$

The position of the nodes of the original point series has been calculated based on the obtained curve, from which a B-spline – a linear element for forming a surface model in SolidWorks – has been formed. The characteristics of the point series belonging to one quarter of the epitrochoid are given in Table 2. The maximum absolute error of the epitrochoid representation (δ_i) was $3.734 \cdot 10^{-4}$ mm.

Fig. 5 shows the contours of the working surfaces of the rotor and the body of the planetary rotor machine, which have been obtained on the basis of the application of the presented methodology.

The initial point series based on which the contours of the rotor and the body have been modelled are formed according to the requirements of the desired interpolation accuracy. This accuracy must exceed the precision with which the CNC can machine the programmed trajectories. For very precise machines (class C), this precision is $1.64 \cdot 10^{-3}$ mm.

The 3D model of the product created using CAD software (SolidWorks) is imported into CAM software (PowerMill). Import of the model is carried out by means of live translators or through neutral formats iges, *x_b*, step, sat ets., transmitting data about surfaces bounding the product. The control program for product machining on CNC is developed using standard CAM functions

Conclusion. The proposed method for modelling surfaces of complex shape using CAD software is based on the formation of contours, representing the curves based on the sur-face determinant with specified accuracy.

Table 1

Source data for forming the rotor profile

Point number, *i*	1	2	3	4	5	6	7	8
Chord length, mm	4.8800	4.6478	4.2183	3.9492	3.8905	3.6769	3.7384	3.3555
δ_i, $\cdot 10^{-4}$ mm	2.781	2.934	2.832	3.366	2.769	3.759	3.150	3.124
Point number, *i*	9	10	11	12	13	14	15	16
Chord length, mm	3.2287	3.1586	3.3749	3.0461	3.6087	3.7523	3.5744	3.7873
δ_i, $\cdot 10^{-4}$ mm	3.708	3.912	3.835	3.734	3.835	4.013	3.962	3.886
Point number, *i*	17	18	19	20	21	22	23	24
Chord length, mm	3.2573	3.6088	3.3715	3.0096	3.6247	3.3424	3.6097	3.4590
δ_i, $\cdot 10^{-4}$ mm	3.759	3.594	3.861	3.594	3.391	3.696	3.607	3.366
Point number, *i*	25	26	27	28	29	30	31	32
Chord length, mm	4.0836	4.3939	4.5235	4.6728	4.8420	4.6255	4.8783	4.6895
δ_i, $\cdot 10^{-4}$ mm	3.670	3.708	3.277	3.442	3.632	3.391	3.289	3.188

Table 2

Source data for forming the body profile

Point number, *i*	1	2	3	4	5	6	7	8	9
Chord length, mm	4.641	4.497	4.481	4.418	4.637	4.088	4.919	4.397	4.307
δ_i, $\cdot 10^{-4}$ mm	3.124	3.340	3.061	2.743	2.997	3.581	3.124	3.366	3.569
Point number, *i*	10	11	12	13	14	15	16	17	18
Chord length, mm	4.731	4.676	3.970	3.786	4.879	5.038	4.587	3.960	4.272
δ_i, $\cdot 10^{-4}$ mm	3.340	2.934	3.353	3.645	3.734	3.353	3.188	3.416	3.480
Point number, *i*	19	20	21	22	23	24	25	26	27
Chord length, mm	4.883	4.662	4.637	5.006	4.602	4.743	4.625	4.846	4.475
δ_i, $\cdot 10^{-4}$ mm	3.124	2.946	3.112	3.251	3.480	3.327	2.972	3.442	3.340

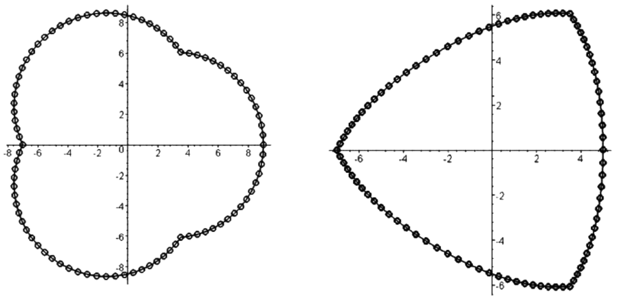


Fig. 5. Contours of the rotor working surfaces and the body of the RPM

The developed algorithms enable determining the original point series belonging to any curve and provide a given interpolation accuracy when forming a contour by a B-spline or by arcs of second-order curves.

Computer models of surfaces of the body and the rotor are formed on the basis of the gear ratio of the planetary rotor mechanism and the rotor dimensions. In order to increase the performance of the compressor, the working surfaces of the rotor have been optimized. The maximum volume of the working chamber has been increased by increasing the radius of the moving gear of the rotary planetary mechanism. In order to prevent the rotor from jamming during compressor operation, the rotor contour has been modified.

The original contour of the formed chain has been replaced by a contour interpolating a point series whose nodes have been determined using a specially designed algorithm. The algorithm is based on determining the mutual contour of the body and rotor at different operation points of the compressor. Modelling of the working surfaces of the compressor required the designing the linear elements of the framework based on a point series obtained from the analytical representation of the curve and the point series obtained structurally.

The disadvantage of the proposed method is that it only aims at forming flat contours. The task of further research is interpolation with specified accuracy of point series belonging to spatial curves.

The solution of this problem will allow increasing the modelling accuracy of guiding curves based on the surface determinant. These are the axial curves of surfaces, the functional purpose of which is transportation of the medium. Such surfaces bound the interblade spaces of turbines, pipeline channels. In addition, it will be possible to form the movement trajectories of the processing tool using CAD software with specified accuracy of location of these trajectories on the surfaces that bound the model of the product designed using CAD software.

The article offers a method for forming computer models of complex surfaces based on a frame consisting of curves, which are absent in CAD libraries.

The study produced the following results:

1. Algorithms for contour formation have been developed, which represent curves defined analytically or structurally with a given accuracy. The obtained contours are used in CAD system as linear elements of the surface model.

2. The developed method has been tested in modelling of the functional surfaces of the rotary planetary compressor. Optimization of the shape of the body profiles has been performed in order to increase its performance. The surface models have been derived from the gear ratio of 3/2, the distance from the centre of the rotor cross-section to its apex is $d = 76$ mm. The radius of the separating chain of the moving gear has been increased from $R = 23.4$ mm in the original model to $R = 29.72$ mm. The values have been compared with the characteristics of the traditional rotary planetary compressor model, in which the rotor is in the form of a Rello triangle. In the original design, the difference between the maximum and minimum volume of the working chamber is 314,300 mm^3, and after optimization the volume difference increased to 337,200 mm^3.

References.

1. Jaberi, A., Yazdi, M., & Sabaapour, M. (2015). Analysis of 3D Passive Walking Including Turning Motions for the Finite-width Rimless Wheel. *Journal of Computational Applied Mechanics*, *46*(1), 63-68. https://doi.org/10.22059/jcamech.2015.53394.

2. Yang, Y., Tang, J., Chen, G., Yang, Y., & Cao, D. (2021). Rub-Impact Investigation of a Single-Rotor System Considering Coating Effect and Coating Hardness. *Journal of Vibration Engineering Technologies, 9*(3), 491-505. https://doi.org/10.1007/s42417-020-00243-0.

3. Ma, H., Zhao, Q., Zhao, X., Han, Q., & Wen, B. (2015). Dynamic characteristics analysis of a rotor–stator system under different rubbing forms. *Applied Mathematical Modelling*, *39*(8), 2392-2408. https://doi.org/10.1016/j.apm.2014.11.009.

4. Páez Chávez, J., Vaziri Hamaneh, V., & Wiercigroch, M. (2015). Modelling and experimental verification of an asymmetric Jeffcott rotor with radial clearance. *Journal of Sound and Vibration*, *334*, 86-97. https://doi.org/10.1016/j.jsv.2014.05.049.

5. Shang, Z., Jiang, J., & Hong, L. (2011). The global responses characteristics of a rotor/stator rubbing system with dry friction effects. *Journal of Sound and Vibration*, *330*(10), 2150-2160. https://doi.org/10.1016/j.jsv.2010.06.004.

6. Wang, S., Hong, L., & Jiang, J. (2020). Characteristics of stick-slip oscillations in dry friction backward whirl of piecewise smooth rotor/stator rubbing systems. *Mechanical Systems and Signal Processing*, *135*, 106387. https://doi.org/10.1016/j.ymssp.2019.106387.

7. Srivastava, A. K., Tiwari, M., & Singh, A. (2021). Identification of rotor-stator rub and dependence of dry whip boundary on rotor parameters. *Mechanical Systems and Signal Processing*, *159*, 107845. https://doi.org/10.1016/j.ymssp.2021.107845.

8. Yu, P., & Chen, G. (2021). Nonlinear modal analysis and its application on prediction of resonance speed for a rotor–stator rubbing system. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *43*(4), 209. https://doi.org/10.1007/s40430-021-02918-5.

9. Yu, P., Chen, G., & Li, L. (2022). Modal analysis strategy and nonlinear dynamic characteristics of complicated aero-engine dual-rotor system with rub-impact. *Chinese Journal of Aeronautics*, *35*(1), 184-203. https://doi.org/10.1016/j.cja.2020.10.031.

10. Zhang, J., Zhang, L., Ma, Z., Wang, X., Wu, Q., & Fan, Z. (2021). Coupled bending-torsional vibration analysis for rotor-bearing system with rub-impact of hydraulic generating set under both dynamic and static eccentric electromagnetic excitation. *Chaos, Solitons & Fractals*, *147*, 110960. https://doi.org/10.1016/j.chaos.2021.110960.

11. Pérez-Arribas, F., & Pérez-Fernández, R. (2018). A B-spline design model for propeller blades. *Advances in Engineering Software*, *118*, 35-44. https://doi.org/10.1016/j.advengsoft.2018.01.005.

12. Khadiv, M., & A Moosavian, S. (2014). A Low Friction Demanding Approach in Gait Planning for Humanoid Robots During 3D Manoeuvres. *Journal of Computational Applied Mechanics*, *45*(1), 47-60. https://doi.org/10.22059/jcamech.2014.52315.

13. Jang, D. J., Kim, Y. Ch., Hong, E. P., & Kim, G. S. (2021). Geometry design and dynamic analysis of a modified cycloid reducer with epitrochoid tooth profile. *Mechanism and Machine Theory*, *164*, 104399. https://doi.org/10.1016/j.mechmachtheory.2021.104399.

14. Karaiev, O., Bondarenko, L., Halko, S., Miroshnyk, O., Vershkov, O., Karaieva, T., ..., & Pristavka, M. (2021). Mathematical modelling of the fruit-stone culture seeds calibration process using flat sieves. *Acta Technologica Agriculturae*, *24*(3), 119-123. https://doi.org/10.2478/ata2021-0020.

15. Lee, S. H., Kwak, H. S., Han, G. B., & Kim, C. (2019). Design of Gerotor Oil Pump with 2-Expanded Cardioids Lobe Shape for Noise Reduction. *Energies*, *12*, 1126. https://doi.org/10.3390/en12061126.

16. Havrylenko, Y., Cortez, J. I., Kholodniak, Yu., Alieksieieva, H., & Garcia, G. T. (2020). Modelling of Surfaces of Engineering Products on the Basis of Array of Points. *Tehnicki Vjesnik – Technical Gazette, 27*(6). https://doi.org/10.17559/TV-20170921112131.

17. Saini, D., Kumar, S., & Gulati, T. R. (2017). NURBS-based geometric inverse reconstruction of free-form shapes. *Journal of King Saud University – Computer and Information Sciences, 29*, 116-133. https://doi.org/10.1016/j.jksuci.2014.12.010.

18. Zhang, Y., Ye, P., Wu, J., & Zhang, H. (2018). An optimal curvature-smooth transition algorithm with axis jerk limitations along lin-

ear segments. *International Journal of Advanced Manufacturing Technology*, *95*, 875-888. https://doi.org/10.1007/s00170-017-1274-1.
19. Pessoles, X., & Rubio, W. (2010). Kinematic modelling of a 3-axis NC machine tool in linear and circular interpolation. *International Journal of Advanced Manufacturing Technology*, *47*, 639-655. https://doi.org/10.1007/s00170-009-2236-z.
20. Havrylenko, Y., Kholodniak, Y., Halko, S., Vershkov, O., Bondarenko, L., Suprun, O., ..., & Gackowska, M. (2021). Interpolation with specified error of a point series belonging to a monotone curve. *Entropy*, *23*(5), 493, 1-13. https://doi.org/10.3390/e23050493.
21. Bilan, T., Kaplin, M., Makarov, V., Perov, M., Novitskii, I., Zaporozhets, A., Havrysh, V., & Nitsenko, V. (2022). The Balance and Optimization Model of Coal Supply in the Flow Representation of Domestic Production and Imports: The Ukrainian Case Study. *Energies*, *15*, 8103. https://doi.org/10.3390/en15218103.
22. Panchenko, A., Voloshina, A., Panchenko, I., Titova, O., & Pastushenko, A. (2019). Reliability design of rotors for orbital hydraulic motors. *IOP Conference Series: Materials Science and Engineering, 708*(1), 012017. https://doi.org/10.1088/1757-899X/708/1/012017.
23. Voloshina, A., Panchenko, A., Panchenko, I., Titova, O., & Zasiadko, A. (2019). Improving the output characteristics of planetary hydraulic machines. *IOP Conference Series: Materials Science and Engineering, 708*(1), 012038. https://doi.org/10.1088/1757-899X/708/1/012038.
24. Al-Quraan, T. M. A., Vovk, O., Halko, S., Kvitka, S., Suprun, O., Miroshnyk, O., ..., & Islam, A. (2022). Energy-Saving Load Control of Induction Electric Motors for Drives of Working Machines to Reduce Thermal Wear. *Inventions*, *7*, 92. https://doi.org/10.3390/inventions7040092.
25. Tabor, S., Lezhenkin, A., Halko, S., Miroshnyk, A., Kovalyshyn, S., Vershkov, O., & Hryhorenko, O. (2019). Mathematical simulation of separating work tool technological process. In *Proceedings of the 22nd International Scientific Conference on Progress of Mechanical Engineering Supported by Information Technology,* POLSITA, Czajowice, Poland, 19–20 September 2019, *132*, 01025. https://doi.org/10.1051/e3sconf/201913201025.

Проектування робочих поверхонь ротаційно-планетарних механізмів

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Мета. Розробка методу згладжування робочих поверхонь статора й ротора з використанням комп'ютерного моделювання для усунення впливу ротора на статор при їх взаємодії.

Методика. Використані спеціальні й загальні методи дослідження: інтерполяція точкових рядів – для визначення вузлів контуру ротора та статора ротаційно-планетарних механізмів; формування B-сплайнів – для побудови ряду точок, координати яких структурно визначені; технологія автоматизованого формування кривих у CAD-системі SolidWorks – для моделювання функціональних поверхонь планетарно-роторного компресора.

Результати. Розроблені алгоритми формування контурів, що представляють аналітично або конструктивно задані криві із заданою точністю. Отримані контури використовуються в системі САПР як лінійні елементи моделі поверхні. Розроблений метод апробовано при моделюванні функціональних поверхонь планетарно-роторного компресора. Проведена оптимізація форми корпусу та профілів ротора з метою підвищення продуктивності роторно-планетарної машини.

Наукова новизна. Розроблені алгоритми дозволяють визначати вихідний ряд точок, що належать будь-якій кривій, і забезпечують задану точність інтерполяції при формуванні контуру B-сплайну або дуг кривих другого порядку. На основі передавального числа планетарно-роторного механізму й розмірів ротора сформовані комп'ютерні моделі корпусних поверхонь ротора. З метою підвищення продуктивності компресора оптимізовані робочі поверхні ротора. Максимальний об'єм робочої камери було збільшено за рахунок збільшення радіуса переміщення шестерні планетарно-поворотного механізму. Для запобігання заклинювання ротора під час роботи компресора змінено контур ротора.

Практична значимість. Розроблено метод моделювання поверхонь складної форми в CAD-системі на основі створення контурів, які із заданою точністю представляють лінії від визначника поверхні. Цей метод дозволяє формувати комп'ютерні моделі складних поверхонь на основі каркаса, що складається із кривих, яких немає в бібліотеках САПР.

Ключові слова: *ротаційно-планетарний механізм, комп'ютерна модель, епітрохоїдальний контур, ротор, статор, передавальне число.*

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