Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2021 vol. 23 no. 4 pp. 65–78
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2021-23.4-65-78

NSTU NETI

Obrabotka metallov -
Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

Investigation of complex surfaces of propellers of vehicles by a mechatronic profilograph

Sergey Vasiliev [a, *], *Viktor Alekseev* [b], *Alyona Fedorova* [c], *Dmitry Lobanov* [d]

I. N. Ulianov Chuvash State University, 15 Moskovsky Prospect, Cheboksary, 428015, Russian Federation

[a] https://orcid.org/0000-0003-3346-7347, vsa_21@mail.ru, [b] https://orcid.org/0000-0002-2780-1727, av77@list.ru,
[c] https://orcid.org/0000-0002-0257-9197, e_a_a@mail.ru, [d] https://orcid.org/0000-0002-4273-5107, lobanovdv@list.ru

ARTICLE INFO

Article history:
Received: 09 September 2021
Revised: 02 October 2021
Accepted: 16 October 2021
Available online: 15 December 2021

Keywords:
Mechatronic profilograph
Complex surfaces
Reverse engineering
Propellers
Vehicles

Funding
The results were obtained under the grant of the President of the Russian Federation for state support of young Russian scientists MD-1198.2020.8, agreement No. 075-15-2020-228

Acknowledgements
Research were conducted at core facility "Structure, mechanical and physical properties of materials".

ABSTRACT

Introduction. The technology of investigation of screw propellers complex surfaces, which include the marine and aircraft propellers of vehicles, mechatronic profilers for the implementation of reverse engineering, is considered. A review of the scientific literature shows that at present the problem of monitoring complex surfaces of products at various stages of its life cycle requires further research, since the use of available devices and methods does not always provide the necessary accuracy, technological effectiveness and sufficient information on measurements. **The purpose of the work** is to develop a new technology for studying complex surfaces of propellers, which include marine and aircraft propellers of vehicles by means of a mechatronic profilograph to implement reverse engineering. **Methods.** The paper considers the implementation of the innovative technology for studying complex surfaces of propellers using the developed mechatronic profilograph. This ingenious mechatronic profilograph is designed to measure the profile and study the shape of complex surfaces of various products, as well as to determine the geometric and morphological parameters of these surfaces. On the basis of theoretical studies the main design and technological parameters are found and the hyperbolic dependence of the angular rate of the laser sensor movement on the scanning radius is determined for the developed mechatronic profilograph. For example, if a constant pitch of the trajectory along the Archimedes spiral is 2 mm, the value of the sensor angular rate should gradually decrease from the maximum value of 2 rad/s to the minimum value of 0.574 rad/s, i.e. by 3.484 times. **Results and discussion.** It is revealed that the use of cylindrical coordinates for processing the obtained data by a profilograph is logical and has a number of advantages. An express analysis of the propeller surfaces with rotary symmetry is carried out and differences in the shapes of the surfaces of the propeller blades by deviation values in the longitudinal and transverse directions for different radii are established. On the basis of the experimental data, a two-factor power model describing deviations with a determination coefficient of 0.967 is obtained, according to its analysis, it is clear that on average the angle of deviation in the perpendicular direction to the radius δ – increases from 0 to 0.3°, and the angle of deviation along the radius γ increases from 0 to 5.4°.

For citation: Vasiliev S.A., Alekseev V.V., Fedorova A.A., Lobanov D.V. Investigation of complex surfaces of propellers of vehicles by a mechatronic profilograph. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2021, vol. 23, no. 4, pp. 65–78. DOI: 10.17212/1994-6309-2021-23.4-65-78. (In Russian).

Introduction

In the manufacturing process, the quality control of products is an important stage. Recently, the quality of products and labor productivity have significantly increased, especially products with complex surfaces, for example, propellers of vehicles. The design of such complex parts and units is carried out at the stage of model development using computer-aided design system in a virtual environment in order to ensure the accuracy and technological effectiveness of the product. It is quite difficult to find and provide the weight

*** Corresponding author**
Vasiliev Sergey A., D.Sc. (Engineering), Associate Professor,
I. N. Ulianov Chuvash State University,
15 Moskovsky Prospect,
428015, Cheboksary, Russia
Tel.: +7-927-843-22-90, **e-mail:** vsa_21@mail.ru

and geometric characteristics of the form surfaces of products right away even using computer-aided design system. At the same time, there is a problem of reliability and diagnostics of these parts and units during operation. For example, breakdowns and failures associated with a violation of the geometry of propellers when coming in contact with foreign objects in air and water are quite possible.

To study complex propeller surfaces of vehicles, reverse engineering using a mechatronic profilograph [1] is proposed. Reverse engineering allows representing a point cloud in the digital form of a physical part or a machine unit. As a rule, a point cloud is topological information about the geometry of a complex surface of a product, which can be used to create its digital model. This method is used quite often when copying machine parts in the absence of design documentation or 3D models, when improving the units with complex surfaces, as well as for creating digital models of products for virtual research in *CAD* liquid media.

The application of reverse engineering methods is relevant in various branches of the national economy: mechanical engineering, agriculture, medicine and others. Therefore, the question of founding a Reverse Engineering Center at the Industrial Development Fund of the Russian Federation was raised by the Minister of Industry and Trade of the Russian Federation *D. V. Manturov* at a meeting of the Government Commission on Import Substitution.

The surface of a complex part is not always perfect, smooth and geometrically correct. More over certain micro- and macro-geometric imperfections can be found on the surface. Waving and surface shape deviations are macro-geometric imperfections of a complex part. The ratio of the pitch deviation to the value of the deviation from the nominal contour is used in the current work to evaluate waving and surface shape deviations. For example, for shape deviation, the ratio of the pitch to the deviation value is more than 1,000.

Profilographs (from “*profile*” and “*graphic*”) are used to specify these parameters in metalworking. They allow measuring surface imperfections and present the results in the form of a profilogram that characterizes the waving, roughness and shape of the surface.

GOST R ISO 4287-2014 “Geometrical Product Specifications (*GPS*). Surface texture. Profile method. Terms, definitions and surface texture parameters” standardizes not only roughness indicators, but also waving, as well as indicators of the primary profile. Therefore, today the transition of machine-building enterprises to *GOST R ISO 4287-2014* is accompanied with a number of difficulties, besides there is a need for new and modern measuring equipment that can generate profilograms to implement the profile method.

Today there are various methods to obtain information on a physical object by means of different data collecting devices. For convenience they can be divided into two groups of methods: contact methods – atomic-force microscopy, stylus profilometry, etc. [2, 3] and non-contact methods – methods that use laser devices, image processing, and others [4–8]. For example, the morphological parameters and the shape of complex surfaces were determined in works [9–11] on mechanical engineering, in works [12–15] for agriculture. A mechatronic profilograph that scans the surface by the cylindrical method has been developed by *S. A. Vasilyev* [16, 17]. The main advantages of this group of methods include the time of obtaining information, its accuracy, convenience and usability of devices. There are also disadvantages that appear in the study of surfaces associated with the phenomenon of diffraction of laser beams on smooth areas, but these errors can be eliminated by program while processing the information [18].

Taking into account the above, we formulate the purpose of the research – the development of a new technology for studying complex surfaces of propellers, which include marine and aircraft propellers of vehicles, mechatronic profilograph for the implementation of reverse engineering.

To achieve this goal, it is necessary to solve the following tasks:

– to propose a technology for studying complex surfaces of propellers of vehicles and the design of a mechatronic profilograph on the basis of the review of reverse engineering methods and measuring devices;

– to develop a mechatronic profilograph; with its application to conduct theoretical and experimental studies of complex surfaces of screw propellers of vehicles; to obtain and process information about their profile;

– to make an express analysis of complex surfaces of products with rotary symmetry and to establish differences in the shapes of the blade surfaces by the deviation values in the longitudinal and transverse directions.

Research method

The designed mechatronic profilograph is proposed as a device for studying complex surfaces of propellers of vehicles (Figure 1). The profilograph is designed to measure the profile and to study the shape of complex surfaces of various products, as well as to determine the geometric and morphological parameters of these surfaces. The device made it possible to obtain a profilogram which estimates undulation, roughness and shape of the surface along the circular trajectory. It can be used in mechanical engineering, as well as in reverse engineering.

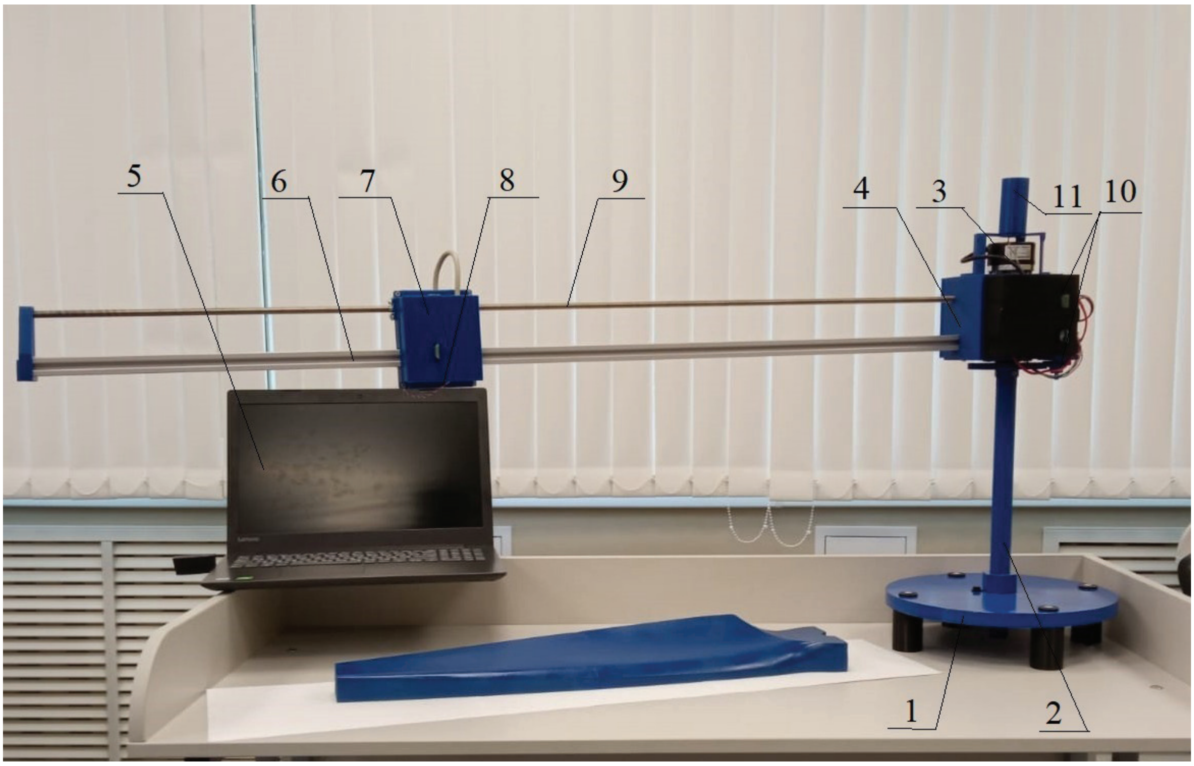


Fig. 1. General view of the profilograph:

1 – base; *2* – rack; *3* – angle sensor; *4* – housing; *5* – laptop; *6* – guide; *7* – carriage; *8* – laser position sensor; *9* – screw; *10* – electric motors; *11* – accelerometer and gyroscope

The mechatronic profilograph consists of:

– a base;

– a rack on which a rotation angle sensor is installed, and in it, with the help of rolling bearings, a housing with a power supply and a control unit is located;

– a fixed support wheel, a satellite communicating with it;

– a laptop equipped with an information measurement system and computer control for coordinated operation of electric motors in the measurement process, as well as a program for receiving and processing indicators of sensors and devices;

– a guide;

– a carriage;

– a laser position sensor;

– a screw;

– electric motors, (a brushed motor *TETRIX® MAX TorqueNADO® Motor W44260* (12 V, DC with a speed of 100 rpm and a torque of 4.9 Nm) and a stepper motor *NEMA 17 42HS48-1684-08AF* (rated current: 1 , 68 A, torque: 5.0 kg/cm, rated voltage: 2.8 V, swing angle / step: 1.8 °) are used);

– an accelerometer;

– a gyroscope.

A stepper motor was chosen to move the carriage, since a high torque is not required, but it is necessary to rotate the console.

The housing is mounted on a rack by means of rolling bearings. Fixed support wheel, a satellite and a motor located on the movable housing are used to rotate it. The laptop is connected with the control unit, sensors and electric motors via Bluetooth radio modules built-in into the laser sensor, a control unit and a laptop.

To perform a structure consisting of a carriage with a laser position sensor, a guide and a screw, a backlash-free bronze nut with manufacturing accuracy *H7*, and a trapezoidal screw with a diameter of 8 mm were used. Moreover, the nut consists of two elements between which a spring is installed. The spring force pushes the elements of the nut away from each other reducing the backlash and the progressive rotation error. The guide, made of T-shaped grooves in an aluminum profile simplifies fixing of the movable carriage during translational movement. Preliminary calculations of the structure strength showed that at a distance of 1 meter with a cantilever mounting of the guide, the deformation grade caused by its own weight is 1.12 mm, and when exposed to a carriage with a sensor weighing 0.15 kg the linear deformation is 1.79 mm.

When checking the mechatronic profilograph, these errors are taken into account, and an external inspection, testing, software check and determination of metrological characteristics are carried out. The mechatronic profilograph was tested using a calibration plate.

The laser sensor is based on the principle of optical triangulation (the maximum data update rate is 2 kHz, the resolution is 0.01 % of the range), and the angular encoder records the cycle of passage of the magnetic pole of a rotating magnet located near the sensing element. The metrological characteristics of the information and measuring system are established: the measuring range of the distance from the sensor to the surface is 100…500 mm, the limits of the permissible absolute measurement error are ± 0.05 % of the range, the measurement range along the circumference is from 0 to 360 degrees, the limits of the permissible error of the angular encoder are ± 30”.

The performance of the mechatronic profilograph: overall dimensions are 1,450x25x550 mm; the change range in the angular velocity of the sensor is 0.1...2.5 rad/s; the change range in the radial velocity of the sensor is 0.0001...0.01 m/s; the supply voltage of the angular encoder of the *E60H* series is 5 V DC, the current consumption is ≤ 80 mA; the number of pulses per revolution is 1,024…8,192, the operating temperature range is –10...+70 °C, the response frequency is up to 300 kHz.

Thus, to implement the profiling of a complex surface, a mechatronic profilograph equipped with an information measurement system is used as a mechatronic measurement system.

To profile a complex surface of parts, a mechatronic profilograph is placed on or near the studied surface on a horizontally positioned table, if the part is small. Accelerometer and gyroscope are used to determine accurately the horizontal surface the laser sensor moves on. For example, compact laser sensors were used during the study. Accelerometer and gyroscope are similar in a way and complement each other, increasing the accuracy of the obtained data. The gyroscope is used to track the position of the laser sensor in space by determining its own angle of inclination relative to the Earth surface. The accelerometer at rest allows calculating the angle of inclination relative to the vector of the Earth gravity. The deviation of the rotation surface of the laser sensor from the level in two perpendicular directions is displayed on the monitor screen in digital form. To correct the horizontal position, the rack is deflected, achieving zero deviations from the horizontal in the longitudinal and transverse directions. For this purpose, for example, the *MPU6050* is used, which is a 3-axis gyroscope and a 3-axis accelerometer in the same housing.

First, a profilograph equipped with an information system determines the profile of a complex surface of a part along a circle that limits the area to be measured. For this purpose the program is run on a laptop and the profilograph is turned on. By means of the control unit, the upper motor moves the laser position sensor along the guide using a screw to the periphery of the measured area, and the lower motor turns the guide to the zero position by rolling the satellite along the fixed supporting wheel. Then, the program starts only the lower motor and the surface is scanned along the periphery of the area. Using a Bluetooth connection, information is transmitted from the sensor with the Bluetooth radio module to the control unit and then to the laptop, both having built-in Bluetooth modules. When the information received the computer program draws a profile along a circle in polar coordinates according to two parameters: the distance between the position sensor and the complex surface of the part, as well as the angle of rotation corresponding to this position from the zero mark according to the angle sensor. The information measurement system of a mechatronic profilograph is a set of functionally integrated technical means such as measuring (sensors), controlling (monitoring and comparison with various profiles models), diagnostic (accelerometer, gyroscope), computing (laptop), control (laptop, electric motors), recording (laptop), displaying (laptop), telecommunications (laptop) and other auxiliary means. This information measurement system is designed to obtain, convert, process and transmit measuring information. It makes a decision on whether the recognized profile belongs to a particular model (smooth, rough, waviness, shaped surface) according to the features that characterize the properties of profiles of complex surfaces (slope, curvature, undulation, roughness). Moreover, for each model, the corresponding trajectory of the sensor movement is used, for example, the Archimedes spiral with a given pitch.

Consider the trajectory of the laser sensor, which is a curve in the form of an Archimedes spiral (Figure 2), the coordinates of which are determined in polar coordinates by the point of the laser sensor $M(r_i, \varphi_i, z_i)$:

$$\begin{cases} r_i = k\varphi_i, \\ z_i = H_i = 0, \end{cases} \tag{1}$$

where r_i – the displacement of M at the angle φ_i from the center of rotation, m; φ_i – the angle of turning of M in i position, rad, z_i – the applicate value of M in i position, m; H_i – the value of the distance to the surface, m, k – the displacement of M at an angle equal to one rad, determined by the formula:

$$k = \frac{S}{2\pi}, \tag{2}$$

where S – the radial pitch of the spiral.

The radial pitch of the spiral S_{rad} is calculated by the formula [1]:

$$S_{\text{рад}} = \left(1 + \frac{Z_2}{Z_1}\right)\frac{Z_5}{Z_4} S_p, \tag{3}$$

where S_p – the pitch of the lead screw; Z_1 – the number of teeth of the satellite 1; Z_2 – the number of teeth of the supporting wheel 2; Z_4 – the number of teeth of the supporting wheel 4; Z_5 – the number of teeth of the satellite 5.

The final equation of the Archimedes spiral (1), taking into account equations (2) and (3), will take the form:

$$\begin{cases} r_i = \dfrac{\left(1 + \dfrac{Z_2}{Z_1}\right)\dfrac{Z_5}{Z_4} S_p}{2\pi} \varphi_i,. \\ z_i = H_i = 0, \end{cases} \tag{4}$$

The coordinates x_i, y_i are related to the angle φ_i in polar coordinates by the formulas:

$$\begin{cases} x_i = r_i \cos\varphi_i, \\ y_i = r_i \sin\varphi_i. \end{cases} \tag{5}$$

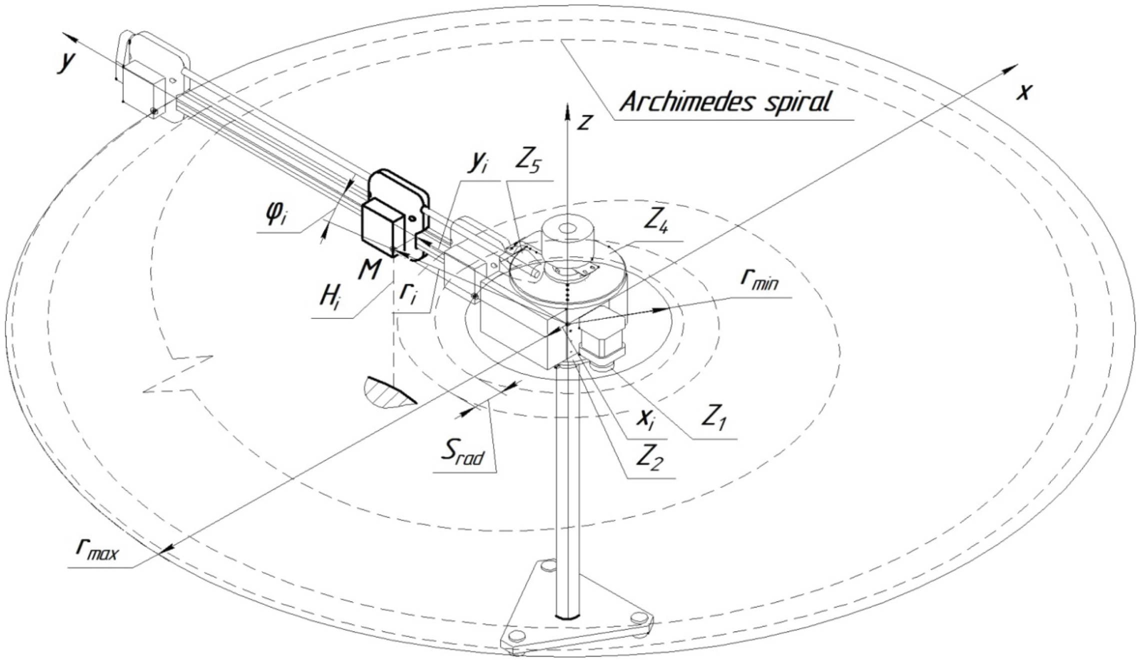


Fig. 2. The trajectory of the *M* point of the laser sensor

With small values of the radial pitch S_p and large values of the scanning radii r_i it is possible to conditionally represent the Archimedes spiral as a set of circles with a pitch *S*. Then the radius *i* of the circle r_i can be determined by the formula:

$$r_i = r_{i\text{-}1} + S, \tag{6}$$

where r_i – the radius of *i* circle at *i* revolution that is equal to the maximum value, r_i; $r_{i\text{-}1}$ – the radius of (*i*–1) circle at (*i*–1) revolution that is equal to the maximum value $r_{i\text{-}1}$,

At the same time, the circumference of the circle will change:

$$L_{\text{o }i} = 2\pi r_i = 2\pi(r_{i\text{-}1} + S). \tag{7}$$

The laser sensor has a fixed frequency of measurement, therefore the circular pitch $S_{\text{o}i}$ of *i* circle at *i* revolution at constant motor speed can be determined by the formula:

$$S_{circ\ i} = \frac{L_{circ\ i}\omega}{2\pi\nu} = \frac{2\pi r_i\omega}{2\pi\nu} = \frac{r_i\omega}{\nu} = \frac{r_i\pi n}{30\nu} i_{13}^{2}, \tag{8}$$

where ν – updating frequency of the laser sensor, Hz; ω – constant angular rate of carrier 6, rad/s; i_{13}^{2} – gear ratio of the cylindrical transmission from satellite 1 to carrier 3, with supporting wheel 2; $L_{circ\ i}$ – length of the *i* circle, mm.

The formula (8) shows that the circular pitch $S_{circ\ i}$ will increase when the motor rotates uniformly and the laser sensor moves away from the center of the profilograph.

Therefore, in order to maintain the stability of the circular pitch on any circle, the movement must be slowed down when motor rotates and the laser sensor moving away from the center.

Then the formula (8) can be rewritten in the following form:

$$S_{circ\ i} = \frac{r_i\omega_{\text{cp}i}}{\nu}, \tag{9}$$

where ω_{cpi} – the average angular rate of the carrier 6 at the *i* revolution, rad/s. To determine the angular rate, we equate the circular pitches at different revolutions:

$$S_{circ\, i} = S_{circ\,(i\text{-}1)}. \quad (10)$$

Considering equation (8), equation (10) will take the form:

$$\frac{r_i \omega_i}{\nu} = \frac{r_{i\text{-}1}\omega_{i-1}}{\nu} = \text{const}, \quad (11)$$

$$\omega_i = \frac{S_{circ}\nu}{r_i}. \quad (12)$$

The equation (12) shows that the numerator has a constant value that depends on the selected parameters: the frequency of updating the laser sensor data set during programming, as well as selected circular pitch set by the user which depends on various measured surface parameters. The denominator is a variable value in the range:

$$r_i \in (r_{\min}, r_{\max}), \quad (13)$$

where $r_{\min}$ – minimum scanning radius that is equal to the outer radius of the profilograph base, m; $r_{\max}$ – maximum scanning radius that is equal to the maximum radius of the profilograph arm, m

The graph of the dependence of the angular rate ω_i on the scanning radius r_i is a hyperbola and is shown in Figure 3, *a*.

The formula (12) for determining the angular rate ω_i depending on the scanning radius r_i with the selected circular pitch S_{circ}, for example, equal to 2 mm and the specified data updating frequency of the laser sensor ν – 100 Hz, will take the form:

$$\omega_i = \frac{S_{circ}\nu}{r_i} = \frac{0.002 \cdot 100}{r_i} = \frac{0.2}{r_i}. \quad (14)$$

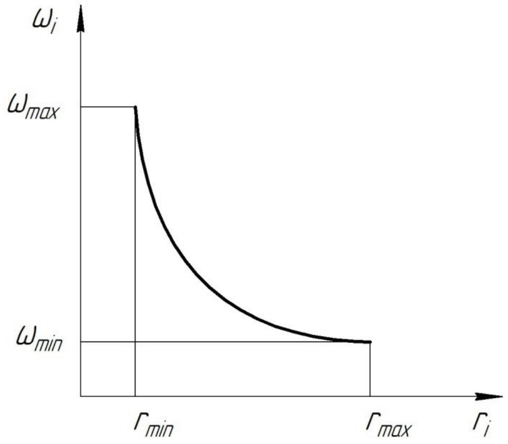
After processing the obtained data in *Excel*, a graph of the dependence of the angular rate ω_i on the scanning radius r_i or on the number of revolutions *N* for the experimental installation of the profilograph was obtained (Figure 3, *b*).

According to the graph obtained with the given technological parameters of the mechatronic profilograph (Figure 3, *b*) it can be concluded that for a constant spiral pitch of 2 mm, the value of the angular rate should gradually decrease from a maximum value of 2 rad/s to a minimum value of 0.574 rad/s. Thus, the technological rate of the measurement operation has decreased by 3.484 times.

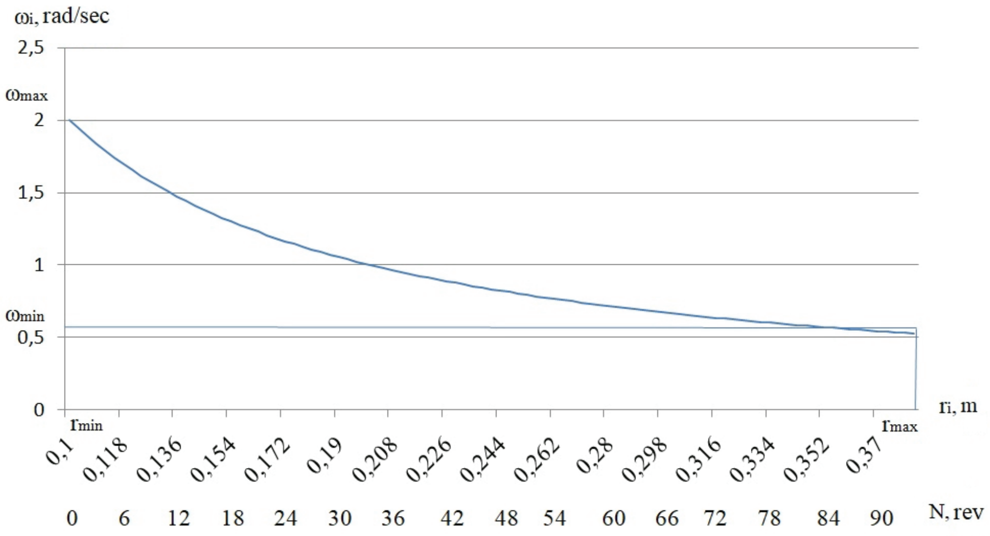
The choice of electric motors was made according to the torque and did not depend on the angular velocity graph. The obtained dependence of the angular velocity on the scanning radius allowed establishing more efficient motor control as part of the drive when scanning the surface along the Archimedes spiral.

When scanning along the Fermat spiral, the first pitch is made along a circle, and the second pitch is made along a spiral, which is a flat curve-the trajectory of a point moving uniformly along the radius vector starting at *O* (Figure 4). The trajectory of the sensor movement along the Fermat parabolic spiral covers optimal area of the plots by a given number of measurement points, which are evenly distributed over the entire area under study. For example, the area of the plot between the first and second turns will be equal to the area of the plot between the second and third turns as well as to the area of the plot between the third and fourth turns, etc.

Next, the profile of the complex surface of the part, in our case it is the blade of the vehicle propeller, is determined along this spiral or curve, moving the laser position sensor from the zero mark and further along a given trajectory. Figure 1 shows one of the stages of reverse engineering, obtaining and verifying a 3D model of a duralumin blade.



a



b

Fig. 3. Graph of the dependence of the angular velocity ω_i on the scanning radius r_i :
a – theoretical, *b* – experimental

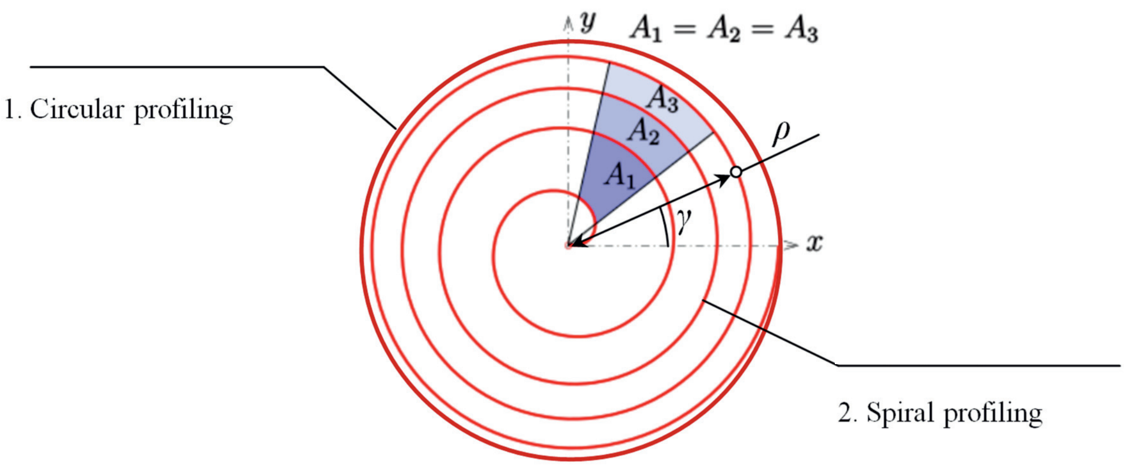


Fig. 4. Trajectory of the sensor movement in a circle and a spiral

The controlled blade is positioned is in the operating range of the sensor. Besides, there should be no foreign objects in the area of incident radiation on the blade and reflected radiation from it. When controlling the blade of a complex shape and texture, the penetration of the mirror component of the reflected radiation into the input window of the sensor should be minimized.

The blade to be measured is placed on a flat surface whether a calibration plate or a table so that the length of blade should not exceed the length of the surface. The blade on a flat surface should not be subjected to any external forces, such as pressure, tension, torsion.

Due to the fact that the information from the sensor is transmitted from each turn of the spiral, there may be an overlap of curves in polar coordinates.

The obtained information is presented with the well-known polar equation of the spiral put in the measurement information system, for example, for the Fermat spiral:

$$r = \sqrt{a^2\varphi}, \tag{15}$$

where r – the radius vector, м; a – the coefficient of the spiral; φ – the angle of the position of the radius vector from the zero mark in degrees.

To translate to the Cartesian coordinate system, use the equations:

$$\begin{cases} x = r\cos\varphi, \\ y = r\sin\varphi, \\ z = z, \end{cases} \tag{16}$$

where x – the longitudinal coordinate, m; y – the transverse coordinate, m; z – the vertical coordinate of the surface of the part at a given point, m.

Results and discussion

The proposed approach significantly simplifies the research even in the case of complex surface shape, the description of which involves the use of special functions (for example, *Riccati*, *Bessel* or *Jacobi*), as well as their combinations. Scanning allows to get a large array of fairly accurate digital data, analyze and select the most adequate digital surface models [19–21].

When scanning objects, the sensor moves over the studied surface along the Archimedean spiral $r = \alpha\varphi$ (or Fermat $r^2 = \alpha^2\varphi$), there is a relatively high speed of surface area processing, since the process is continuous and there is no need to reduce the speed due to stops, associated with shuttle scanning. In the developed device the pitch of the spiral is selected according to each specific problem situation and can be quite small. Therefore, even a linear model allows achieving high accuracy of description for adjacent points of the studied surface not to mention nonlinear variants. Experience shows that models with $R^2 > 0.99$ are selected relatively quickly and easily, i.e. less than 1 % of statistical data is not described by the selected formulas. And these figures should be considered taking into account the fact that defects of the objects, such as various chipping, bends, etc., lead to at least 5…10 % discrepancies in the data. With the help of data extrapolations it is possible to obtain the functions describing the surface taking into account the necessary conditions. This can be data in a Cartesian coordinate system, as well as data with a constant polar angle, a constant radius, or any other conditions. If it is necessary to make some changes, the values calculated from the functions can be compared with those directly scanned, since the developed device can scan along any given trajectory.

One of the options for practical use can be an express analysis of the state of the surface of objects with rotary symmetry. The use of cylindrical coordinates is appropriate in this case and has the following advantages:

– tracking the dynamics of changes in the distance H along the polar radius r at a constant polar angle φ, in the form of functions $\varsigma_\varphi(r)$. They are obtained by selecting values corresponding to certain polar angles from the data array. Pitch $\Delta\varphi$ between the polar angles is chosen on the basis of the specific goals of the study;

– tracking the dynamics of the change in the shape of the distance H along the polar angle φ at a constant polar radius r, in the form of functions $\xi_r(\varphi)$. They are obtained from the data array by selecting values corresponding to certain values of the radius with a necessary pitch Δr.

In general, the simultaneous use of $\varsigma_\varphi(r)$ and $\xi_r(\varphi)$ for surface analysis makes it possible to study the "evolution" of the surface shape with radial or angular displacement along each propeller blade. Thus, the defects of the pressure and suction surfaces of each blade, leading and trailing edges, can be evaluated quite quickly and easily: the number, area, maximum depth and the average volume of chipping. Further, defects in the shape of the blades are evaluated and the shapes of different blades are compared with each other, studying deviations, bends or deformations in the radial and perpendicular directions as well as the differences in the areas of the blades.

As mentioned above, high values of determination coefficients of the models describing the surface make it possible to extrapolate effectively data and move from one coordinate system (r_i, φ_i, H_i) to another (x_k, y_k, z_k).

In addition to formula (16) , when recalculating areas and volumes, it should be remembered that the Jacobian transition

$$J(r;\, \varphi\, ,H) = \begin{vmatrix} x'_r & x'_\varphi & x'_H \\ y'_r & y'_\varphi & y'_H \\ z'_r & z'_\varphi & z'_H \end{vmatrix} = r, \qquad (17)$$

that is $dS_{xyz} = rdS_{r\varphi H}$, and $dV_{xyz} = rdV_{r\varphi H}$.

After the experimental data are obtained, they are divided into arrays. For each blade, the "smoothness/roughness" is estimated by analyzing the ΔH_i – deviations of the experimental values from the values calculated by regression dependencies. According to the values that statistically significantly exceed the average deviation on the surface, the boundaries of chipping and other defects are determined, and then its parameters are calculated: area, maximum depth, average volume based on the approximation, the cavity of a ball bearing or elliptical segment.

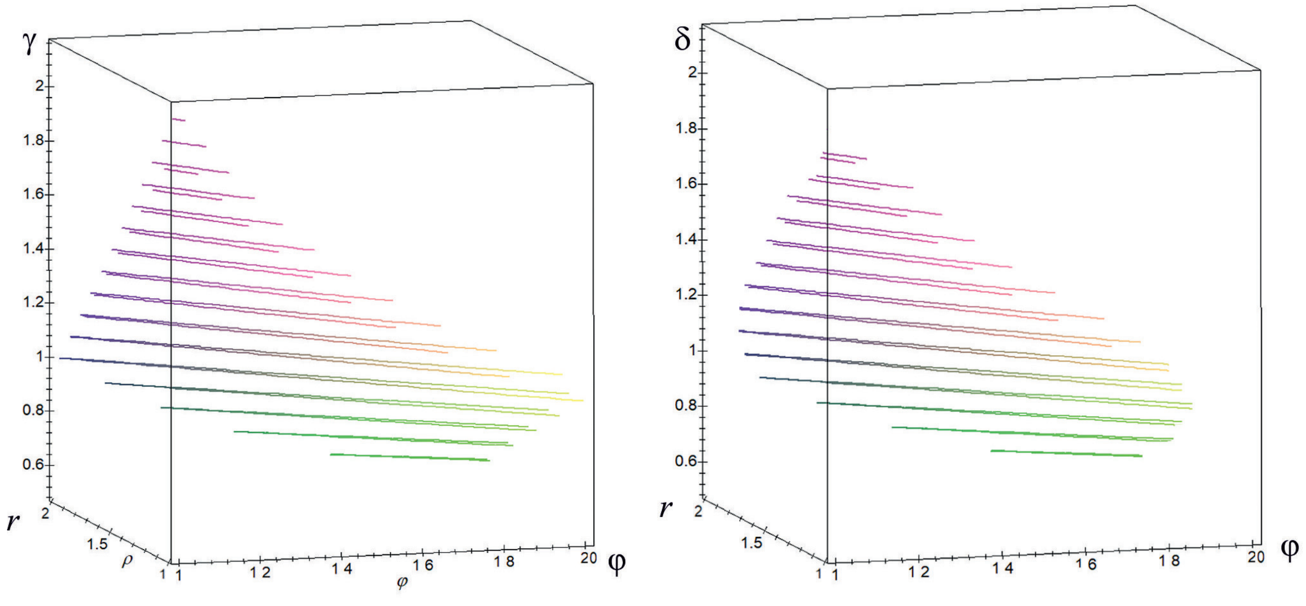
The next stage is to study the differences in the shapes of the blades surfaces. To implement it, the data corresponding to the same values of the radius r when the angle φ changes along each blade are compared, and vice versa the data corresponding to the same values of the angle φ when the polar radius r changes along each blade are compared, that is, the functions $\varsigma_\varphi(r)$ and $\xi_\rho(\varphi)$ are used. Denoting the deviations in the values between j and k blade by Δz_{jk}, both the deviation values along the radius γ, and δ – the angle of deviation in the direction perpendicular to the radius can be determined.

For propellers with axially variable pitch (the pitch of the helical lines varies both along the axis and along the radius), the angle between the curves of the adjacent blade surfaces corresponding to the same values of radii changes, the distances between the curves increase as well.

Taking into account the results of experimental studies and considering the array of deviation values ΔH_i for the corresponding points of different propeller blades, the dependence of the increase in deviations from the polar radius and angle is obtained (Figure 5).

A two-factor power model, describing the deviation with the coefficient of determination $R^2 = 0.967$, has the form $H = 1.071\times10^{-4}\mathrm{r}^{5.487}\varphi^{9.017}$, with an average angle of deviation perpendicular to the radius direction δ increases from 0 to 0.3°, and the angle of deflection along the radius γ increases from 0 to 5.4°.

Thus, studying complex surfaces of propellers of vehicles by reverse engineering using the developed mechatronic profilograph, we specified its design and technological parameters, made an express analysis of the surfaces of propellers with rotary symmetry and found out differences in the shapes of the surfaces of the propeller blades by the deviation values in the longitudinal and transverse directions for different radii.



a *b*

Fig. 5. Determination of deviation values:
a – γ; *b* – δ

Conclusions

1. A new method for studying complex surfaces of propellers of vehicles and the design of a mechatronic profilograph based on a review of reverse engineering methods are proposed.

2. On the basis on theoretical studies, the main design and technological parameters are specified and the hyperbolic dependence of the angular rate of the laser sensor movement on the scanning radius is established for the developed mechatronic profilograph. For example, for a constant pitch of the trajectory along the Archimedes spiral of 2 mm, the value of the angular rate of the sensor should gradually decrease from the maximum value of 2 rad/s to the minimum value of 0.574 rad/s, i.e. by 3.484 times.

3. An express analysis of the surfaces of propellers of vehicles with rotary symmetry is made and differences in the shapes of the surfaces of the propeller blades are specified by the deviation values in the longitudinal and transverse directions for different radii. Based on experimental data, a two-factor power model describing deviations with a determination coefficient of 0.967 is obtained, according to its analysis, it is clear that, on average, the angle of deviation in the perpendicular direction to the radius δ increases from 0 to 0.3°, and the angle of deviation along the radius γ increases from 0 to 5.4°.

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Conflicts of Interest

The authors declare no conflict of interest.