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HARMONIC DRIVES WITH HIGH ACCURACY AND SERVICE LIFE, WORKING IN DIFFERENT FIELDS

Master's Program Automation of design and engineering

The abstract of the Master's Thesis

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The thesis work is done at the Federal State Autonomous Education Institution of Higher Education «Siberian Federal University»

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INTRODUCTION

The topicality of thesis. Increasing the frequency of communication and navigation devices requires an increase in the accuracy of antenna drives. Ensuring the accuracy of pointing of space communications antennas is one of the most important tasks of space engineering. However, the tooth is actively worn out during usage. Since it is difficult to form oxide films on the metal surface due to the lack of oxygen. Therefore, the main causes of failure of wave gears are loss of accuracy and increase in start torque due to the abundance of wear products in the lubricant.

The task of increasing the resource can be solved in various ways: varying the geometric parameters, the choice of materials of gears and lubricant, the use of additional methods of thermal, chemical, mechanical treatment (or a combination thereof). Then, if choose as the criterion for varying geometric parameters the minimum wear in vacuum, then the important task is to determine the contact pressures and the speed of sliding for each tooth surface.

The purpose of thesis is solving the problem of increasing the wear resistance of a harmonic drive operating in a vacuum by selecting the wave generator geometric parameters.

There are several **tasks** to reach this purpose:

1. Finding the profile of a wave generator that ensures minimum wear, including in vacuum
2. Carry out an analysis of the wear model applicability in terms of the effect of the wear rate coefficient on the wear value
3. Analysis of mesh quality in the meshing zone for adequate contact simulation
4. Development of a finite-element model for analyzing the nature of the gear mesh.

Research methods.

1. The method of block search for finding the solution of nonlinear functions;
2. Method of the elasticity theory for the evaluation of the stress-strain state;
3. Method of finite element modeling in the ANSYS Workbench.

Reliability of the data is determined by the selected methods of solving the problems posed, preliminary verification of the parameters of the computational model, and by numerical experiment.

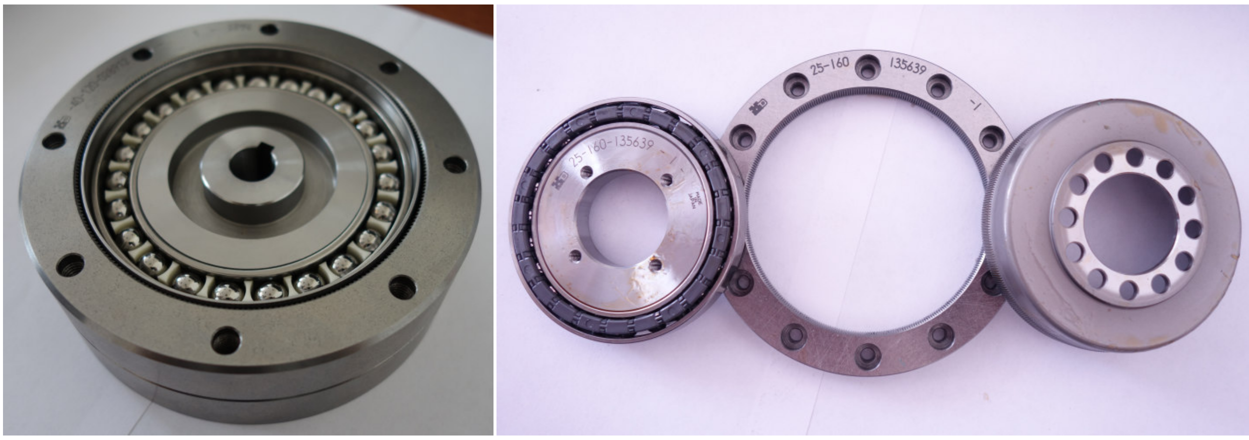
Subject of investigation is a harmonic drive (HD), included in the drive of the antenna of the spacecraft. The figure below shows the two main common constructions.

The scientific novelty.

The approach to the estimation of the wave generator geometrical dimensions influence through evaluation of wear by the finite element method.

The practical significance of thesis.

The developed design model allows selecting the wave generator form providing the increased wear resistance, including under vacuum conditions, at the design stage of the harmonic drive, which allows maintaining the drive's operability, which includes this HD to maintain its efficiency by the criterion of ensuring accuracy.



a) b)

Figure 1 – Harmonic drive: a – HD with short flexspline; b – HD with short «cup»-type flexspline

Personal contribution of the author.

1. Software has been developed for the automated gears design that are part of the HD

2. The effect of the wave equation review on engagement the quality.

3. The size of the finite element mesh is determined, which ensures the quality contact pressures simulation in the zone of normal (non-edge) contact

4. A computational model has been developed for finite element simulation of the HD parts interaction.

Place of thesis realization. "Design - engineering support of machinery production" department, Polytechnic Institute of Federal State Autonomous Educational Institution of Higher Professional Education "Siberian Federal University".

Place of International internship: «CADFEM GmbH» (Grafing near Munich, Germany)

Approbation of thesis results.

Main provisions of the thesis and its individual sections reported at:

- International Scientific Conference “Reshetnev readings”, section “Mechanics of special systems”, in 2012, 2013 and 2015 (Krasnoyarsk)
- International conference “Svobodny Prospect 2017”, section “Implementation of CADCAMCAE Systems”, in 2016 (Krasnoyarsk)

Published works. Results of thesis are presented in 5 publications.

CONTENTS OF THESIS

Introduction. Grounded the importance of the thesis work, formulated the goals and tasks of the research and defined objects and subjects of research.

The first chapter of the thesis work: it is devoted to the review of techniques for increasing the resource, assessing the operability and determining the geometric parameters of the harmonic drive, and their analysis by the finite element method. The works of Russian scientists, such as Ginzburg E.G., Ivanov M.N., in which approaches to the design calculation of wave gears are formulated. In the works of Timofeev G.A., Kostikov Yu.V., Lyuminarskii S.E. and Luminarsky I.E. approaches to the estimation of the kinematic accuracy and the intrinsic error of the harmonic drive are formed. In the works of foreign scientists (Rathindranath M., Rhéaume F-E., Xiaoxia Ch), the results of the investigation of the torsional stiffness of the HD are presented, including using the finite element modeling. And considered constructive solutions presented in foreign patents for the authorship of Ishikawa, which describes the main advantages of the new manufacturing circuit used by company HarmonicDrive AG. Based on the survey, a method was developed for determining the geometric parameters of a harmonic drive of design stage.

In addition, a review was made of methods for estimating the wear resistance of contacting metal surfaces, with the purpose of estimating the HD resource by the wear resistance test (Drozdov Yu.N., Kragelskiy IV). As the basis for the model of volumetric wear estimation, the Archard model was used, which is implemented in the ANSYS finite element simulation software package.

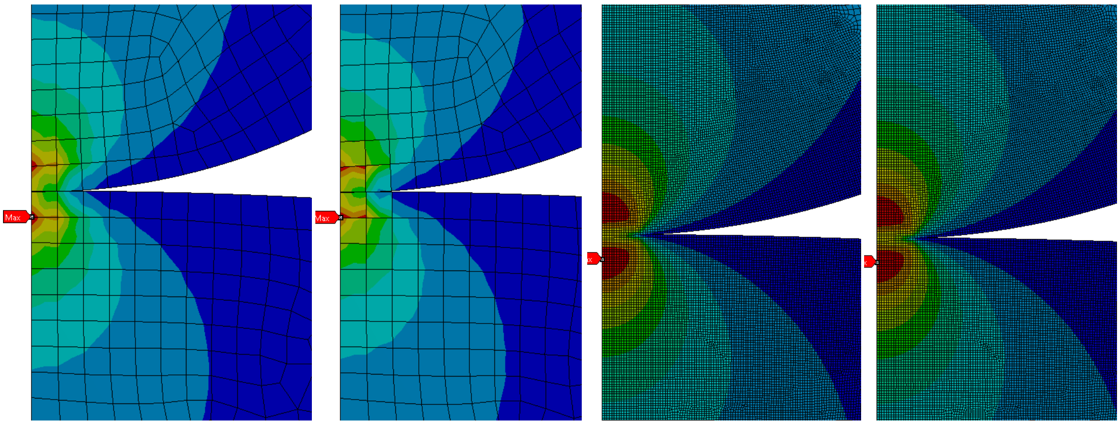
The second chapter is devoted to the evaluation of the element size influence on the contact pressures obtained. The size of the element is estimated from the condition that the calculated contact pressures for a plane problem (in 2d formulation), in a plane-strain state with an analytical solution of the Hertz problem for the contact of the cylinders. The criteria for estimating the quality of the tooth mesh also used the condition that the averaged and non-averaged stresses coincide (Figure 2).

Below is an equation describing the amount of worn-out material in the ANSYS software suite, which corresponds to the Archard model:

$$w = \frac{K}{H} p^m v^n,$$

where *K* – wear coefficient, *H* – material hardness, *p* – pressure, *v* –velocity, *m* and *n* – pressure and velocity exponent.

For this equation, the effect of the value of the coefficient *K* on the volumetric wear is estimated. In addition, direct dependence is revealed.



a) b) c) d)

Figure 2 – Mesh quality analysis results: a – course mesh, average mean stress; b – course mesh, no average mean stress; c – fine mesh, average mean stress; d - fine mesh, no average mean stress

The third chapter is devoted to the evaluation of the effect of equations of equal velocity curves on which an external profile of the wave generator is constructed, on the quality of the tooth mesh: i.e. on such parameters as the number of teeth in meshing, the distribution of the gap in the loaded and unloaded gear (Figure 3).

The calculation was carried out with the geometry of the wave generator that described following equations:

$$r(\varphi) = r_0 + w_0 \cdot \cos(2\varphi) \tag{1}$$

$$r(\varphi) = r_0 + w_0 \cdot (\cos(2\varphi) + k \cdot \sin^2(4\varphi)) \tag{2}$$

$$r(\varphi) = \begin{cases} r_0 + \left(\frac{w_0}{A-4/\pi}\right)(A\cos(\varphi) + \varphi\sin(\beta)\sin(\varphi) - 4/\pi) \\ r_0 + \left(\frac{w_0}{A-4/\pi}\right)(Bsin(|\varphi|) + \left(\frac{\pi}{2} - |\varphi|\right)\cos(\beta)\cos(\varphi) - 4/\pi) \end{cases} \tag{3}$$

where r_0 – initial radius of wage generator; w_0 – HD deformation coefficient; β - angular coordinate of the «deformation force»; k – coefficient of additional deformation; coefficients: $A = \sin(\beta) + \left(\frac{\pi}{2} - \beta\right)\cos(\beta)$, $B = \cos(\beta) + \beta \cdot \sin(\beta)$.

Below is a calculation model of a harmonic drive, it consists of a wave generator, a flexible and rigid gears. In the case of a simulation of the transmission, which includes a coupling half, also by analogy with a rigid wheel, a half-coupling is modeled. On the figure below shown the tooth contact of a flexible wheel with a hard tooth (Figure 3). When the moment direction is counterclockwise, the right side of the contact zone is contacted by the edges of the flexible wheel teeth, and the left part by the edges of the rigid wheel.

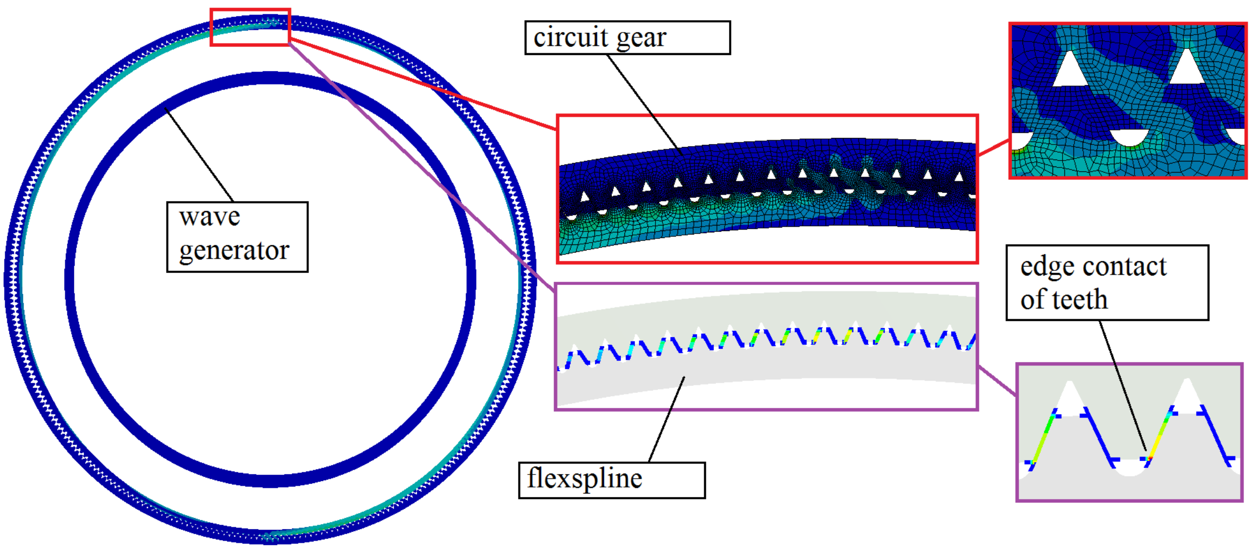
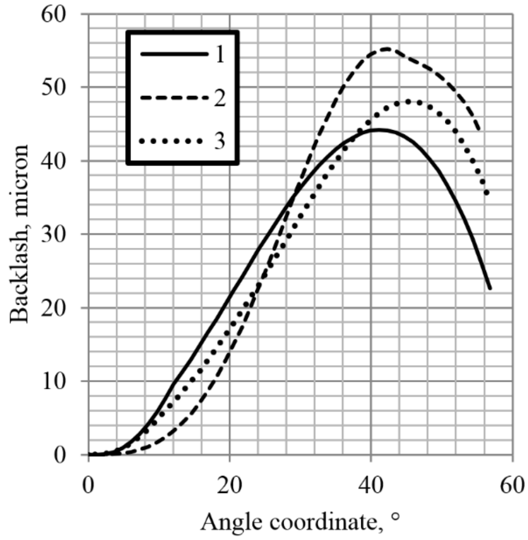
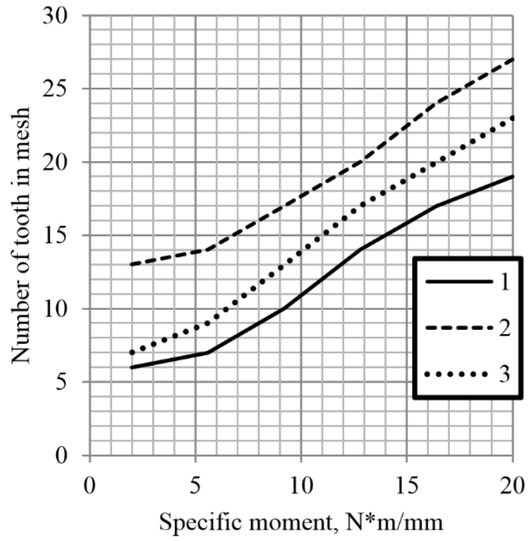


Figure 3 – Results of calculations of equivalent and contact stress

For the developed model of the harmonic drive, the number of teeth in the gearing and the side gap was estimated. In addition, since one of the reasons for the failure of a flexible wheel is its breakdown along the cavity of the teeth, an estimate was made of the maximum equivalent stresses in the tooth cavity that are alternating. The obtained results showed that the use of a modified waveform generator, with increased profile curvature in the "frontal" zone, leads to an increase in these stresses. However, as shown in the diagram to the left, the transmission with the profile described by equation number two (2) has lower maximum contact pressure.

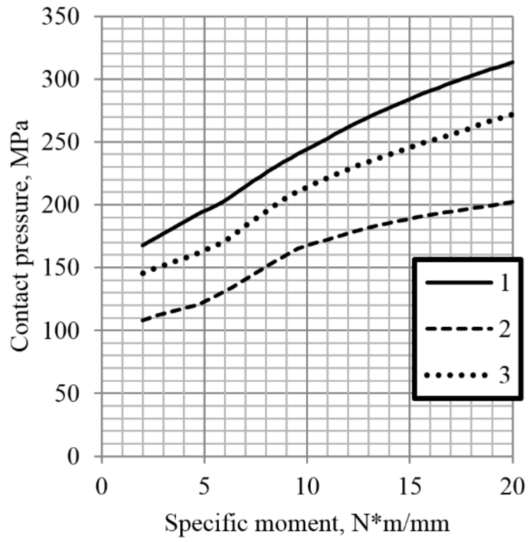
Below are the results of calculating the wear for the harmonic drive. The wave generator then oscillates in a sinusoidal law with an amplitude of three degrees. The results are shown in the form of graphs, showing the distribution of the maximum contact pressures for the upper meshing zone. The results of the distribution of the averaged stresses are also given, along which it is possible to judge the distribution of forces between the teeth.

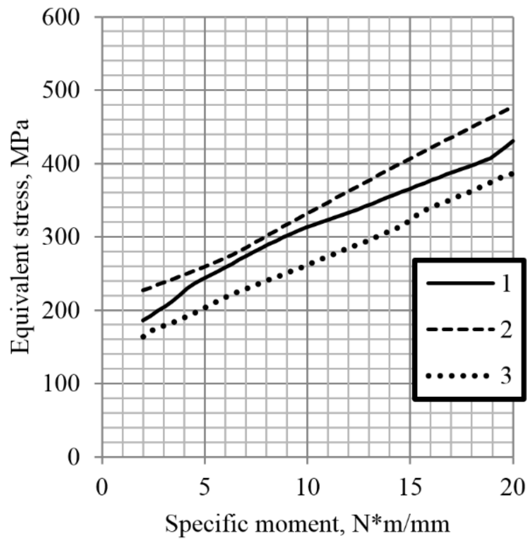




a) b)

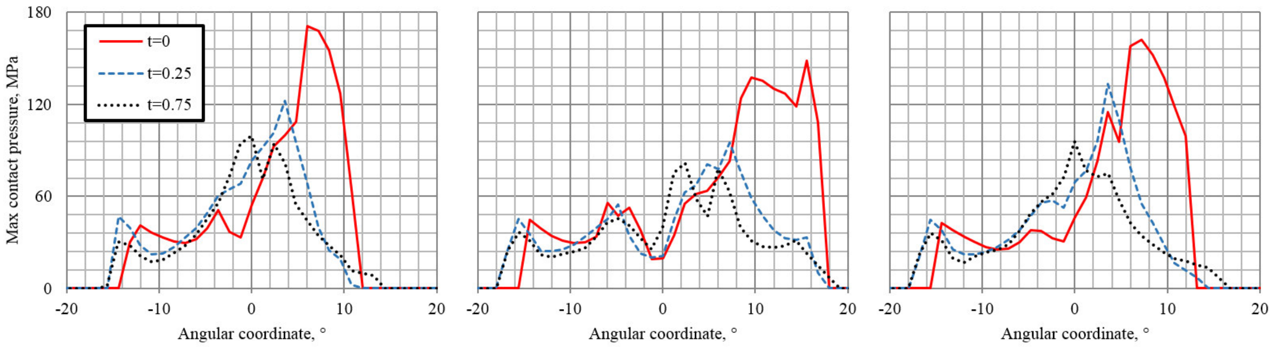
Figure 4 - Results: a – teeth backlash; б – number of teeth in contact: for profiles 1 - «cosine»; 2 – «cosine-sinus»; 3 - profile deformed by 4 forces





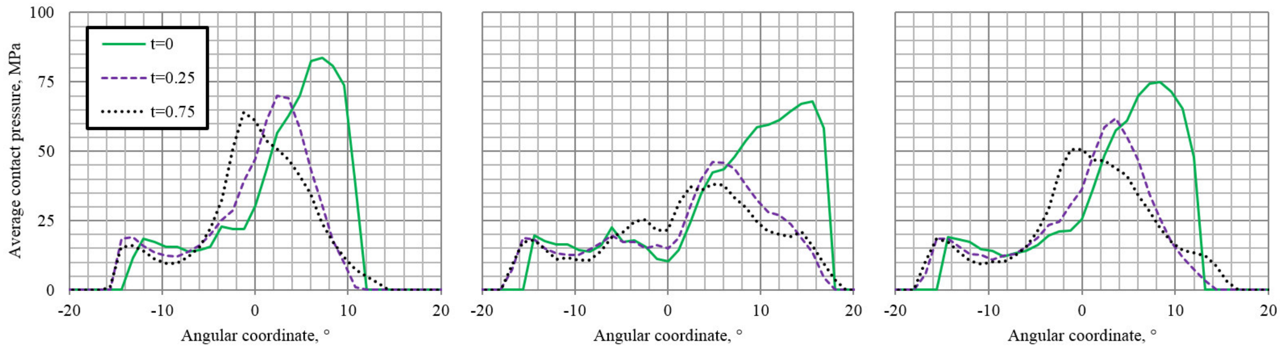
a) б)

Figure 5 - Results: a – contact pressure; б – equivalent stress in the tooth cavity of flexspline: for profiles 1 - «cosine»; 2 – «cosine-sinus»; 3 - profile deformed by 4 forces



a) b) c)

Figure 6 – Distribution of contact pressure: a - «cosine»; b – «cosine-sinus»; c - profile deformed by 4 forces



а) б) в)

Figure 7 – Distribution of averaged contact pressure: a - «cosine»; b – «cosine-sinus»; c - profile deformed by 4 forces

The figure below shows the growth of volumetric wear over time. It can be seen that in the case of the application of the modified profile (2), a 1.5-times decrease in volumetric wear is observed.

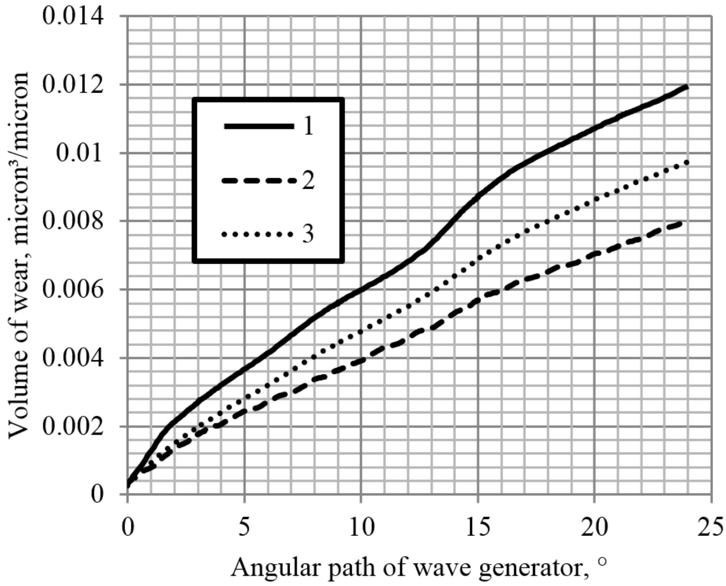


Figure 8 – Volumetric wear of HD for profiles: 1 - «cosine»; 2 – «cosine-sinus»; 3 - profile deformed by 4 forces

Because of teeth lateral surfaces wear process of the HD, the following values of the output shaft additional rotation were obtained: 16.5 arc seconds for the profile of the wave generator made with a "cosine"; 11.91 seconds of arc for "cosine-sinus"; 13.67 angular seconds for a profile deformed by four forces. The obtained results correlates with the values of wear test, obtained earlier.

CONCLUSION

In the course of the thesis work, a calculation model was developed to determine the nature of the contact interaction and determine the magnitude of the teeth lateral surfaces volume wear. In the course of analyzing the results of model with different wave generator shapes simulation. It is determined that when the shape of the profile corresponding to the "cosine-sine" profile is observed a greater number of teeth in meshing, less pressure and less wear of the teeth. At the same time, during wear, the meshing zone with high loads is dislocated relative to the frontal zone, which prevents wear due to sticking under standstill load.

In the future, it is planned to conduct a numerical experiment under harmonic drive various operating conditions, in particular, under the action of the maximum operating torque. Also with the direction of the moment co-directed with the angular velocity vector of the wave generator to simulate the flexspline teeth interference when entering into contact, due to its extension.

MAIN PROVISIONS OF THESIS ARE PUBLISHED IN THE FOLLOWING PAPERS:

1. Lukin R.S., Usakov V.I., Vavilov D.V., Iptyshev A.A. [Modeling the interaction of the wave gear units]. *Vestnik SibGAU*. 2013. no. 1. p. 118-122. (In Russ.)
2. Usakov V.I., Lukin R.S. [Profile of the wave generator as the control parameter in modeling wave gear] *Reshetnev readings*. 2013. vol. 1. no 17. p. 300-301. (In Russ.)
3. Lukin R.S., Kozlova N.I. [The choice of instruments to implement a methodology design harmonic drive with given output characteristics]. *Reshetnev readings*. 2014. vol. 1. no 18. p. 300-302.
4. Vavilov D.V., Lukin R.S., Usakov V.I. [Method of designing gear drive mechanism of different purpose]. *Reshetnev readings*. 2014. vol. 1. no 18. p. 280-282.
5. Vavilov D.V., Lukin R.S., Usakov V.I. [Method of designing gear drive mechanism of different purpose]. *Vestnik SibGAU*. 2015. vol. 16. no 1. p. 35-40.