UDC 621.9.08
Doi: 10.31772/2712-8970-2024-25-2-248-255

Для цитирования: Карабонцева М. В., Брижинская Н. В., Левко В. А. Автоматизация контроля геометрических характеристик червячных и конических зубчатых колес при помощи координатно-измерительных машин // Сибирский аэрокосмический журнал. 2024. Т. 25, № 2. С. 248–255. Doi: 10.31772/2712-8970-2024-25-2-248-255.

For citation: Karabontseva M. V., Brizhinskaya N. V., Levko V. A. [Automation of controlling the geometric characteristics of worm and bevel gears using coordinate measuring machines]. *Siberian Aerospace Journal.* 2024, Vol. 25, No. 2, P. 248–255. Doi: 10.31772/2712-8970-2024-25-2-248-255.

Автоматизация контроля геометрических характеристик червячных и конических зубчатых колес при помощи координатно-измерительных машин

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Статья содержит результаты исследований по автоматизации контроля геометрических характеристик зубчатых колес. Применение координатно-измерительных машин позволяет существенно повысить производительность и точность измерений. Однако их применение для контроля зубчатых колес требует использования специальных программ для проведения и обработки результатов измерений изделий со сложной формой поверхности. Использование для метрологического контроля геометрических характеристик червячных и конических зубчатых колес программного обеспечения позволяет достичь высокой точности проведения контрольно-измерительных работ. Для автоматизации контроля геометрических характеристик червячных и конических зубчатых колес создан дополнительный модуль к стандартной программе. С его помощью все точки измеряемой криволинейной поверхности зубчатых колес, полученные контактным методом по типовой программе измерений, структурируются в единый массив данных с протоколом измерений. На основе этих данных модуль формирует профиль измеренной поверхности зуба колеса и выстраивает геометрический контур профиля измеряемого зуба. Результатом работы модуля является формирование общего профиля всего зубчатого колеса и его сравнение с исходным (теоретическим) профилем зубчатого колеса в целом. Сам процесс контроля осуществляется в небольшом временном интервале, что позволяет использовать предложенный подход к автоматизации контроля профиля зубчатых колес в мелкосерийном производстве.

Ключевые слова: координатно-измерительная машина, зубчатое колесо, отклонение профиля зуба, автоматизация контроля.

Automation of controlling the geometric characteristics of worm and bevel gears using coordinate measuring machines

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The paper contains the results of research on the automation of controlling the geometric characteristics of gears. The use of coordinate measuring machines can significantly increase the productivity and accuracy of measurements. However, their use for controlling gears requires the application of special programs for carrying out and processing measurement results of products with complex surface shapes. The use of software for metrological control of the geometric characteristics of worm and bevel gears makes it possible to achieve high accuracy of control and measurement work. To automate the control of geometric characteristics of worm and bevel gears, an additional module has been created for the standard program. With its help, all points of the measured curved surface of gears, obtained by contact method according to a standard measurement program, are structured into a single data array with a measurement protocol. On the basis of these data, the module generates a profile of the measured surface of a wheel tooth and builds a geometric contour of the measured tooth profile. The result of the module's operation is the formation of a general profile of the entire gear and its comparison with the original (theoretical) profile of the gear as a whole. The control process itself is carried out in a short time interval, which makes it possible to use the proposed approach to automating the control of gear profiles in small-scale production.

Keywords: coordinate measuring machine, gear wheel, tooth profile deviation, control automation.

Introduction

Currently, all production processes must meet strict criteria and ensure the manufacturing of products of the required quality and dimensional accuracy. These requirements are especially relevant for the manufacturing of parts with a complex (curvilinear) shape, including worm and gear wheels. These parts have high production costs and labor intensity, and the requirements for the manufacturability of their design are high [1].

Errors in the manufacturing of gears lead to increased dynamic loads, vibration, noise in gearboxes and premature failure of mechanisms. GOST 1643–81 contains more than 20 accuracy parameters of cylindrical gears, divided into four accuracy standards: kinematic accuracy, smooth operation, tooth contact and side clearance. At the machining stage, the main problem, as a rule, is obtaining a tooth profile that corresponds to the declared degree of accuracy [2].

In the manufacturing of parts with curved surfaces, various technological processes are widely used, including processes for controlling geometric dimensions. In mass production conditions, manual operations for controlling the geometric parameters of curved surfaces do not meet the requirements for stability and reliability of measurements, as well as their performance. In this case, it is possible that random measurement errors caused by the human factor may occur. In this regard, at the modern level of industrial production, technological control processes using coordinate measuring machines (CMMs) are widely used. These control means are characterized by a high degree of versatility and small values of passport errors. They can be used to solve a wide range of tasks - from part inspection to certification of technological equipment. However, passport data on CMM errors can be attributed to only a small number of the simplest measured geometric parameters, while the rest of the majority cannot be unambiguously characterized [3].

Modern CMMs, used to measure the coordinates of surface points of manufactured models (parts), are high-precision devices that provide six degrees of freedom when moving and orienting the measuring probe in space. Controlled by a computer or manually by an operator, they are equipped with developed libraries of programs for measuring products of various shapes and processing measurement results. First of all, they consist of standard geometric objects, such as flat curvilinear contours made up of segments of straight and conic sections, as well as spatial ones - planes, prisms, bodies of revolution, etc. Along with this, taking measurements and processing their results in relation to products with a complex surface shape are not sufficiently provided, especially when it is necessary to separately control specific controlled parameters [4]. In this regard, measuring the main parameters of gears and threaded parts on a CMM is a non-trivial task [5; 6].

The best solution today is to check gears and gear cutting tools on universal gear measuring centers (GCs). Such centers have the ability to directly measure not only the errors of the profile, direction, pitch and radial runout, but also the topology of the tooth surface, as well as the shape and location of the surfaces of the part itself. Gear measuring centers make it possible to measure all geometric parameters of a cylindrical gear ring according to the main domestic and international standards, which is necessary when setting up CNC machines in modern gear-processing production [7].

However, the use of gear measuring centers pays off only in conditions of large-scale and mass production of gears at specialized enterprises. For the manufacturing of products that include worm and bevel gears in small-scale production, it is preferable to use standard CMMs using special approaches to measurement processes [8].

Directions for automation of controlling geometric characteristics of gear wheels

The efficiency and reliability of coordinate measurement processes equally depends on both the technical and metrological characteristics of the basic CMM hardware and the functionality of specialized metrological software [9; 10].

The use of CMMs with various types of measuring heads and tips to control the geometric parameters of gears is advisable due to the fairly high accuracy. This technology makes it possible to determine and construct the involute and profile angle of an Archimedean worm with an error of 2–3 μm [11].

Controlling gear wheels with error recording can significantly increase the accuracy and objectivity of two-profile control of gear wheels, expand the information base for assessing the quality of gear wheels and carry out targeted selection of gear wheels with the required properties. Equipping the recording device of the measuring interaxial distance (MID) with additional programs allows for statistical processing of the measurement results of gear wheels and finding correlations between the MID parameters and such elemental errors of the gear wheel as the error in the direction of the tooth, the error in the angle of the original contour, the tooth thickness error, the tooth profile error [12].

The problem of combining all measurement results to construct a general gear profile is solved on the basis of a universal software module that allows automated control of the required parameters, regardless of the type of a CMM and the type of a gear [13].

The main recommendations for the development of such a module are given in the paper, which considers the methodological basis for constructing programs, mathematical dependencies, and an approximate diagram of the movements of the measuring element [14–16]. However, they are aimed at automating the measurement of involute spur gears.

Automation of controlling the geometric characteristics of worm and bevel gears using coordinate measuring machines is possible using standard software. When measuring on a CMM using this software, the tooth tip cone or root cone is automatically measured for adjustment (alignment). When entering the gear parameters (number of teeth, pressure angle at the gear pole, gear module, cone angles of the part, etc.), an exemplary flank surface is created from the gear parameters.

The next step in the controlling process is to create exemplary flank surfaces by topographic measurement. In this case, the pitch with the thickness of the tooth, lateral and profile lines is assessed. Next, the deviation of tolerances for the mutual arrangement of wheel surfaces (radial runout, deviation from alignment) is controlled. As a rule, one contact sensor is used for measurement, and the measurement itself is implemented without a rotary table. The result of the measurements is a set of data on the overall deviation of the tooth profile.

However, processing measurement results in this software product does not imply visualization of the geometric contour of the profile of the tooth being measured, as well as the construction of a general profile of the entire gear with its subsequent comparison with the original model. The purpose of this work was to create an additional module for this program to solve the problems described above.

Additional module to the standard program

To automate the control of geometric characteristics of worm and bevel gears, an additional module to the standard program was written. With its help, all points of the measured curved surface of gears, obtained by the contact method according to a standard measurement program, are structured into a single data array. In this case, a measurement protocol is automatically generated. The error of linear measurements in this case is 0.1 µm. A general profilogram of tooth profile deviation is determined (Fig. 1) and a profilogram of total and individual tooth profile deviations is formed (Fig. 2).

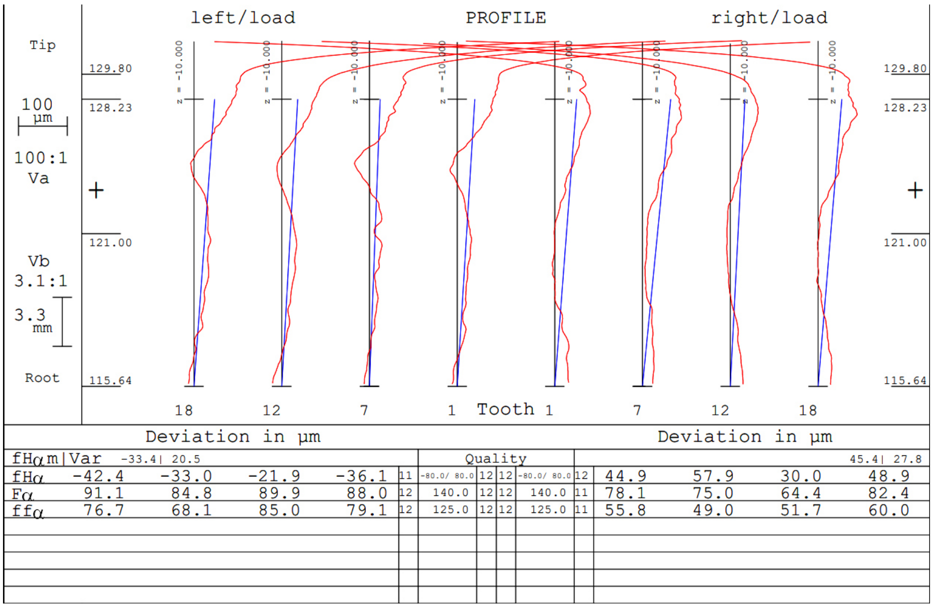

Рис. 1. Общая профилограмма отклонения профиля зуба

Fig. 1. General profilogram of tooth profile deviation

The measurement protocol data is original. On the basis of these data, the developed module generates a profile of the measured tooth surface of a bevel (worm) wheel and builds a geometric contour of the profile of the measured tooth (Fig. 3). For this construction, functions for working with geometric variables and converting them into various data types are used. This allows not only generating an array of points describing spatial surfaces, but also performing various types of calculations with it. The results of these calculations are used both to construct a general (total) profile of the entire gear and to compare it with the original (theoretical) profile of the gear.

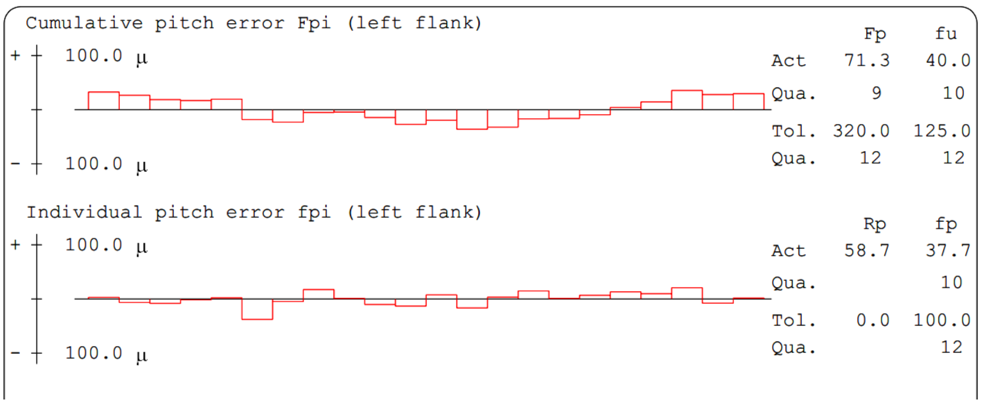

Рис. 2. Профилограмма суммарных и отдельных отклонений профиля зуба

Fig. 2. Profilogram of total and individual deviations of the tooth profile

Next, on the basis of the obtained profiles of all the gear teeth, a general (total) profile of the entire gear is formed using a special module. The resulting profile is compared with the original (theoretical) gear profile.

On the basis of the measurement protocol and visualization of the profile of the measured surface, a conclusion is made about the compliance (deviation) of the controlled geometric dimensions of worm and bevel gears from those specified in the technical documentation, including tolerances for the relative position of the wheel surfaces.

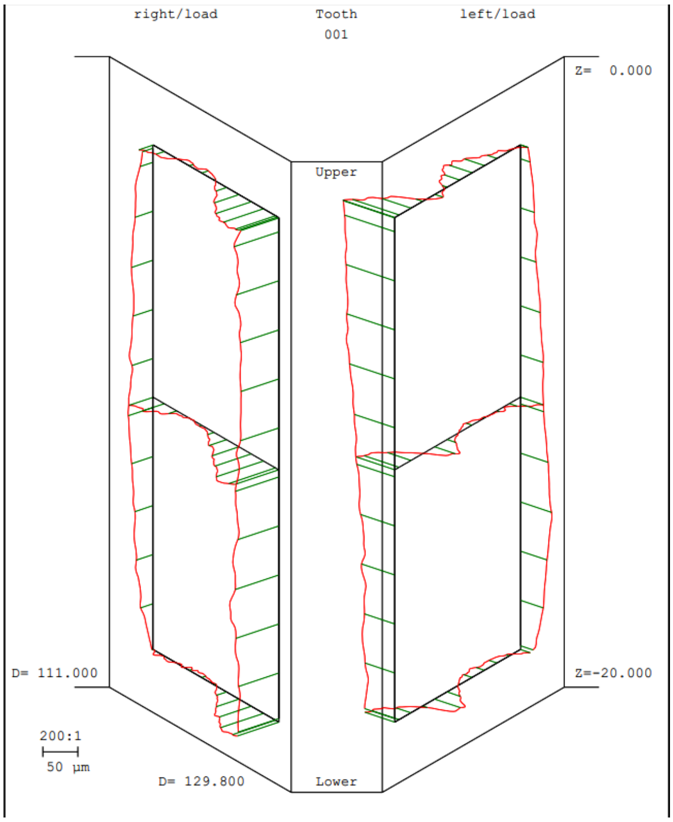

Рис. 3. Геометрический контур профиля измеряемого зуба конического колеса

Fig. 3. Geometric contour of the bevel gear tooth profile being measured

The process of controlling the geometric characteristics of worm and bevel gears is carried out in a short time interval, which makes it possible to use the proposed approach to automating the control of gear profiles in small-scale production.

Conclusion

The proposed approach to automating the control of geometric characteristics of worm and bevel gears using the created additional module to standard software makes it possible to increase the productivity of this process and implement it on standard coordinate measuring machines. The formation of a single data array of all points of the measured curved surface of a worm or bevel wheel tooth with their subsequent integration into a common wheel profile allows one to quickly carry out the technological control process by comparing the measured profile with the theoretical one.

This approach ensures high accuracy (up to 0.1 μm) and speed of the gear control process (halving the time for the measurement process) in small-scale production.

Библиографические ссылки

1. Сысоев С. К., Сысоев А. С., Левко В. А. Технология машиностроения. Проектирование технологических процессов. СПб.: Лань, 2016. 288 с.

2. Ковальчук С. Н. Контроль зубчатых колес на координатно-измерительной машине GLOBAL // Вестник Кузбасского гос. техн. ун-та. 2014. № 5(105). С. 124–126.

3. Болотов, М. А., Чевелева А. О., Жидяев А. Н. Оптимизация методик измерения геометрических параметров деталей ГТД при их контроле на КИМ // Вестник Самарского гос. аэрокосм. ун-та им. академика С. П. Королёва (нац. исследоват. ун-та). 2011. № 3-3(27). С. 100–105.

4. Методика оценки точности изготовления аэродинамических моделей по материалам измерений на координатно-измерительной машине / М. А. Архангельская, В. Д. Вермель, В. Ф. Забалуев и др. // Ученые записки ЦАГИ. 2014. Т. 45, № 5. С. 78–90.

5. Kinematics of point-conjugate tooth surface couple and its application in mixed mismatched conical worm drive / Q. Meng, Y. Zhao, J. Cui et al. // Mechanism and Machine Theory. 2022. Vol. 167. P. 104528. DOI: https://doi.org/10.1016/j.mechmachtheory.2021.104528.

6. Тигнибидин А. В., Зайнуллина Л. В., Ромащенко В. А. Определение достоверных методик проведения измерений на координатно-измерительных машинах // Динамика систем, механизмов и машин. 2018. № 1 (6). С. 171–191.

7. Плиско О. П., Попова В. А., Николаева Е. В. Измерение зубчатых колес и резьбовых деталей на координатно-измерительной машине // Стандартизация, метрология и управление качеством : мат. Всеросс. науч.-техн. конф., посвященной 90-летию Росстандарта и 170-летию метрол. службы России. Омск, 2015. С. 133-135.

8. Береснева А. В. Применение CAI-системы PowerINSPECT и портативной CimCore Infinite 2.0 для измерения корпусов спироидных редукторов // Теория и практика зубчатых передач и редукторостроения: сб. докл. науч.-практ. конф. Ижевск, 2017. С. 27–32.

9. Park N. G., Lee H. W. The spherical involute bevel gear: its geometry, kinematic behavior and standardization // J Mech Sci Technol. 2011. Vol. 25. P. 1023–1034. DOI: https://doi.org/10.1007/s12206-011-0145-1.

10. Сурков И. В., Волков Д. А. Развитие координатной метрологии в России // Станкостроение и инновационное машиностроение. Проблемы и точки роста : мат. Всеросс. науч.-техн. конф. Уфа, 2018. С. 322–327.

11. Никольский С. М. Контроль зубчатых колес с применением современных средств измерений // Изв. Тульского гос. ун-та. Технические науки. 2022. № 4. С. 395–399. DOI: 10.24412/2071-6168-2022-4-395-399.

12. Антонюк В. Е., Русецкий В. Н. Возможности современных средств двухпрофильного контроля зубчатых колес // Вестник Полоцкого гос. ун-та. Сер. В. Промышленность. Прикладные науки. 2009. № 8. С. 101–105.

13. Ушаков М. В., Воробьев И. А., Никольский С. М. Анализ результатов расчета точек измерительной траектории при контроле зубчатых колес // Отечественный и зарубежный опыт обеспечения качества в машиностроении: сб. докладов IV Всеросс. науч.-техн. конф. с междунар. уч. Тула, 2023. С. 46–49.

14. Ушаков М. В., Воробьев И. А., Никольский С. М. Рекомендации по разработке методики контроля зубчатых колес на КИМ // Контроль. Диагностика. 2022. Т. 25, № 9(291). С. 46–51. DOI: 10.14489/td.2022.09. pp.046-051.

15. Ушаков М. В., Воробьев И. А., Никольский С. М. Алгоритмизация процесса обработки измерительной информации при контроле зубчатых колёс на координатно-измерительных машинах // Альманах современной метрологии. 2022. № 3(31). С. 154–159.

16. Applied iterative closest point algorithm to automated inspection of gear box tooth / S. Boukebbab, H. Bouchenitfa, H. Boughouas, J. M. Linares // Computers & Industrial Engineering. 2007. Vol. 52, Is. 1. P. 162–173. DOI: https://doi.org/10.1016/j.cie.2006.12.001.

References

1. Sysoev S. K., Sysoev A. S., Levko V. A. *Tekhnologiya mashinostroyeniya. Proyektirovaniye tekhnologicheskikh protsessov* [Mechanical engineering technology. Process engineering]. St. Petersburg, Lan Publ., 2016, 288 p.

2. Kovalchuk S. N. [Control of gears on the GLOBAL coordinate measuring machine]. *Vestnik Kuzbasskogo gosudarstvennogo tekhnicheskogo universiteta*. 2014, No. 5(105), P. 124–126. (In Russ.)

3. Bolotov M. A., Cheveleva A. O., A. N. Zhidyaev [Optimization of methods for measuring the geometric parameters of gas turbine engine parts when monitoring them on coordinate measuring machines]. *Vestnik Samarskogo gosudarstvennogo aerokosmicheskogo universiteta im. akademika S. P. Korolova (natsional'nogo issledovatel'skogo universiteta)*. 2011, No. 3-3(27), P. 100–105. (In Russ.)

4. Arkhangelskaya M. A., Vermel V. D., Zabaluev V. F. et al. [Methodology for assessing the accuracy of manufacturing aerodynamic models based on measurement materials on a coordinate measuring machine]. *Uchenyye zapiski TSAGI*. 2014, Vol. 45, No. 5, P. 78–90. (In Russ.)

5. Meng Q., Zhao Y., Cui J. et al. Kinematics of point-conjugate tooth surface couple and its application in mixed mismatched conical worm drive. *Mechanism and Machine Theory*. 2022, Vol. 167, P. 104528. DOI: https://doi.org/10.1016/j.mechmachtheory.2021.104528.

6. Tignibidin A. V., Zainullina L. V., Romashchenko V. A. [Determination of reliable methods for carrying out measurements on coordinate measuring machines]. *Dinamika sistem, mekhanizmov i mashin*. 2018, No. 1 (6), P. 171–191. (In Russ.)

7. Plisko O. P., Popova V. A., Nikolaeva E. V. [Measurement of gears and threaded parts on a coordinate measuring machine]. *Standartizatsiya, metrologiya i upravleniye kachestvom: Materialy Vserossiyskoy nauchno-tekhnicheskoy konferentsii, posvyashchennoy 90-letiyu Rosstandarta i 170-letiyu metrologicheskoy sluzhby Rossii.* [Standardization, metrology and quality management: Materials of the All-Russian scientific and technical conference dedicated to the 90th anniversary of Rosstandart and the 170th anniversary of the metrological service of Russia]. Omsk, 2015, P. 133–135. (In Russ.)

8. Beresneva A. V. [Application of the CAI-system PowerINSPECT and portable CimCore Infinite 2.0 for measuring housings of spiroid gearboxes]. *Teoriya i praktika zubchatykh peredach i reduktorostroyeniya: Sbornik dokladov nauchno-prakticheskoy konferentsi* [Theory and practice of gears and gear engineering: Collection of reports of a scientific and practical conference]. Izhevsk, 2017, P. 27–32. (In Russ.)

9. Park N. G., Lee H. W. The spherical involute bevel gear: its geometry, kinematic behavior and standardization. *J Mech Sci Technol*. 2011, Vol. 25, P. 1023–103. DOI: https://doi.org/10.1007/s12206-011-0145-1.

10. Surkov I. V., Volkov D. A. [Development of coordinate metrology in Russia]. *Stankostroyeniye i innovatsionnoye mashinostroyeniye. Problemy i tochki rosta: Materialy Vserossiyskoy nauchno-tekhnicheskoy konferentsii* [Machine tool building and innovative mechanical engineering. Problems and growth points: Materials of the All-Russian Scientific and Technical Conference]. Ufa, 2018, P. 322–327. (In Russ.)

11. Nikolsky S. M. [Testing of gears using modern measuring instruments]. *Izvestiya Tul'skogo gosudarstvennogo universiteta. Tekhnicheskiye nauki*. 2022, No. 4, P. 395–399. DOI 10.24412/2071-6168-2022-4-395-399.

12. Antonyuk V. E. Rusetsky V. N. [Possibilities of modern means of dual-profile control of gears]. *Vestnik Polotskogo gosudarstvennogo universiteta. Seriya V. Promyshlennost'. Prikladnyye nauki*. 2009, No. 8, P. 101–105. (In Russ.)

13. Ushakov M. V., Vorobyov I. A., Nikolsky S. M. [Analysis of the results of calculating points of the measuring trajectory when monitoring gears]. *Otechestvennyy i zarubezhnyy opyt obespecheniya kachestva v mashinostroyenii: IV Vserossiyskaya nauchno-tekhnicheskaya konferentsiya s mezhdunarodnym uchastiyem: sbornik dokladov* [Domestic and foreign experience in quality assurance in mechanical engineering: IV All-Russian scientific and technical conference with international participation: collection of reports]. Tula, 2023, P. 46–49. (In Russ.)

14. Ushakov M. V., Vorobyov I. A., Nikolsky S. M. [Recommendations for the development of methods for monitoring gear wheels on CMMs]. *Kontrol'. Diagnostika*. 2022, Vol. 25, No. 9(291), P. 46–51. DOI: 10.14489/td.2022.09. pp.046-051.

15. Ushakov M. V., Vorobyov I. A., Nikolsky S. M. [Algorithmization of the process of processing measurement information when monitoring gears on coordinate measuring machines]. *Al'manakh sovremennoy metrologii*. 2022, No. 3(31), P. 154–159. (In Russ.)

16. Boukebbab S., Bouchenitfa H., Boughouas H., Linares J. M. Applied iterative closest point algorithm to automated inspection of gear box tooth. *Computers & Industrial Engineering*. 2007, Vol. 52, Is. 1, P. 162–173. DOI: https://doi.org/10.1016/j.cie.2006.12.001.

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