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ANALYSIS OF ERRORS OCCURRING DURING TOOTH MILLING OPERATIONS AND TECHNOLOGICAL SYSTEM FACTORS AFFECTING THE ACCURACY OF TOOTH PROCESSING

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Abstract: The article discusses the issues of determining and analyzing errors in the formation of gears by gear hobbing in the conditions of large-scale machine-building production. An analysis of some errors was carried out. The work identified the following main types of errors that arise during the machining of gears: radial, tangential, axial, producing surfaces. Each of these types has been analyzed in sufficient detail, and a table of the influence of errors in the technological system on the main parameters of the producing surface of the tool has been compiled. In addition, the work analyzes and systematizes the factors of the technological system that affect the accuracy of the formation of gears. All errors are considered in one small period of time and then approximated in time. This approach avoids the problem of heterogeneity of errors. Thus, a generalized universal model of the structure of machine errors is formed. Next, by obtaining mathematical models for each error, a model of the errors of the technological system is formed. The article provides a classification of hob gear cutters. Here we distinguish involute, convolute and Archimedean cutters. The article states that the errors in the relative positions of each conjugated point of the generating and machined contours are composed of: a) errors in the relative position of the tool and the workpiece in space, created by inaccuracies in the manufacture and setup of the machine and fixtures, as well as inaccuracies in the rolling movements; b) errors in the profile of the generating contour (tool) itself. It is indicated that in the manufacture of gears using the profile copying method, the errors of the tool itself and the location of the tool and the workpiece on the machine, the geometric accuracy and rigidity of the machine are of greatest importance. When machining gears using the rolling method, the kinematic and dynamic accuracy of the machine increases. An analytical dependence is provided—a formula—that considers a combination of factors affecting the accuracy of the tooth profile to varying degrees. The provisions put forward in this work in terms of accounting and systematization of gear machining errors play an important role. In conclusion, the article provides recommendations for improving the quality of processing of gear teeth, as well as constructing a three-dimensional model of the interaction of three elements of the technological system: machine - hob gear cutter - workpiece.

Keywords: *gears, gear machining, machining errors, gear cutting tools.*

Introduction.

One of the important tasks facing researchers is the ability to control the precision of manufacturing parts. Error minimization is a special case of part manufacturing quality management.

Ensuring the accuracy of gears at the stages of roughing is an integrated task, the solution of which depends on many parameters: technological preparation of production, applied processing methods, technical and technological discipline in production.

Research.

The task facing the researchers is to determine the dependencies of the precision of the toothed crown on the errors of the technological system, tool, basing, workpiece, etc.

These include the manufacturing error of the worm cutter (f_{fr}), the error of installing the milling cutter on the machine ($f_{\text{ins.fr.}}$), blank error ($f_{\text{workp.}}$), the error of installing the workpiece on the machine ($f_{\text{ins.workp.}}$), machine error ($f_{\text{mach.err.}}$), measurement error ($f_{\text{meas.}}$).

In accordance with GOST 1643-81, *the error of the* f_{fr} tooth profile is the normal distance between the two nominal end profiles closest to each other, between which the actual end active profile of the tooth of the gear is placed. The actual end profile of a tooth is understood as the line of intersection of the actual lateral surface of the tooth of a gear wheel with a plane perpendicular to its working axis [1].

Thus, the calculated error of the tooth profile of the gear is a function of:

$$f_{fr.calc.} = F(f_{fr}, f_{inst.fr.}, f_{\text{workp.}}, f_{\text{ins.workp.}}, f_{\text{mach.err.}}, f_{\text{meas.}}) \quad (1)$$

In accordance with GOST 1643-81, the tolerance for tooth profile error f_{f}.

Accordingly:

$$f_f \geq f_{fr.calc.} = F(f_{fr}, f_{inst.fr.}, f_{\text{workp.}}, f_{\text{ins.workp.}}, f_{\text{mach.err.}}, f_{\text{meas.}}) \quad (2)$$

After analyzing the existing error calculation methods, the following were identified:

1. Systematic errors:

- errors of the workpiece- errors of manufacture, basing;
- machine errors- errors in the manufacture of individual components and their relative location, taking into account their wear during operation;
- errors resulting from the forces and moments acting during processing.

2. Random errors- uneven properties of the material of the workpiece, tool, etc.

Random errors have an effect on the occurrence of scattering of the workpiece sizes processed under the same conditions [2, 3, 4, 5]. The size dispersion is due to many random causes that cannot be accurately determined beforehand and that manifest themselves simultaneously and independently of each other. Such reasons include fluctuations in the hardness of the workpiece material, fluctuations in the temperature regime of processing, elastic squeezing of the elements of the technological system under the influence of cutting forces, etc.

The analysis shows that processing errors are not fully taken into account when calculating dimensional chains. Moreover, the errors selected manually from the reference literature are not systematized, implicit, automatic calculations of dimensional circuits, taking into account the errors that occur during machining, are insufficiently developed.

Automated calculation of errors in this case is difficult, because it is necessary to simultaneously take into account the causes of errors and the laws of their change over time. It is proposed to consider the process of forming the lateral surface of the tooth of the gear ring of the wheel at a specific time, and then the resulting functional dependencies change over time. In this case, all errors can be considered static. Random errors at a particular time can be taken as constant values. The dynamic errors under these conditions depend only on the cutting parameters.

Accounting for errors and determining the type of their relationship can be achieved by introducing intermediate coordinate systems (IC). According to the differentiation method, errors are identified that occur at a certain level, starting from the coordinate system of the machine further towards the tool and the workpiece to the cutting point. The beginning of the SC node shows the spatial position of this node relative to the coordinate systems of the previous nodes and the machine as a whole.

Each CI characterizes a specific i-th node of the machine tool system, thus the error of the i-th link is unambiguously described in the corresponding SC. And the interrelationships of the SC with each other determine the accumulated error. Geometrically, the accumulated error is a vector with a beginning in the (i-1)-th SC and an end in the i-th SC. The choice of the origin of coordinates for each SC is carried out in accordance with the standard coordinate system of the gear milling machine, which minimizes errors and reduces the number of SC.

In order to determine the "degree of contribution" of the error of a particular node to the total error, all intermediate errors are systematized on the one hand according to the object of influence of the error - the location of the workpiece or tool. In order to ensure the completeness of information about errors, the differentiation (detailing) of the technological operation into individual elements is carried out according to the method of differentiation of TP into structural elements.

Differentiation is carried out by "sequential movement" from the point of contact between the tool and the workpiece, moving from the consideration of microsystems to macrosystems. An error vector is calculated at each level (as the geometric sum of all error vectors taken into account at this level).

All errors are considered in one small period of time and then approximated in time. This approach makes it possible to circumvent the problem of heterogeneity of errors. Thus, a generalized universal model of the machine error structure is formed. Further, by obtaining mathematical models for each error, a model of the errors of the technological system is formed.

Consider the static error of the profile of a worm gear cutter.

Roughing of the gear rings of cylindrical wheels is mainly carried out by worm gear cutters.

The cutting edges (RC) of worm cutters are located on the surface of the coils of various types of worms. These worms are called the main ones.

As is known, depending on the type of the main worm, worm gear cutters are classified as involute, convolute and Archimedean.

The exact geometric shape of the main worm is determined by the condition of proper engagement of this worm and the gear wheel. Since proper engagement with an involute gear wheel forms only one type of worm- an involute worm, an involute worm must be adopted for theoretically accurate profiling of the worm.

The main advantage of this worm is the presence of an involute profile in the end section, and a complex curved profile in the axial or normal section to the turns of the worm. Therefore, theoretically correct profiling of the worm cutter will be ensured when the cutting edges are positioned on the surface of the coils of the involute worm [6].

However, at present, in the manufacture of worm cutters, the main worms are used, which are shaped approximately according to Archimedean or convolute worms.

The worm closest to the involute, Archimedean, is distinguished by a rectilinear trapezoidal profile in the axial section and a curved profile along the Archimedean spiral in the end section. This feature makes it easy to manufacture and control Archimedean worm cutters.

The convolute worm has a rectilinear trapezoidal profile in a normal section along the turn, or in the hollow of the turns. In the same sections, a profile is set for worm cutters profiled on the basis of convolute worms.

In general, the theoretical profile of the cutting edge of a worm gear cutter, which is the line of intersection of the main involute screw and the front flat surface, is curved. Since the manufacture of a cutter with a curved RC of a given profile is quite difficult, in practice their profile is approximated by a straight line, a circular arc, three rectilinear sections or a hyperbola [7, 8].

In the article Lazebnik I.S. [9], the organic error of the profile of the cutting edge of the milling cutter resulting from processing is considered.

The simplest and most common in practice is the profiling method, which consists in approximating the theoretical profile of the RC by a straight line segment. However, the value of the OP may be unacceptably large. If the approximating straight line passes through a point lying on the average calculated cylinder and is tangent to the theoretical profile of the RC at this point, then the maximum OP is observed at the points of the RC furthest from the specified point.

The accuracy of the profile of the RC worm cutter depends not only on the profiling method, but also on the method of backing the teeth.

The most common is radial backing with a disk circle, in which the angle Σ of the intersection of the axes of the cutter and the circle is equal to the angle (γ_{mo}) lifting the helical line of the main worm of the milling cutter on the middle design cylinder. With this method of backing, there is an error in the profile of the milling cutter tooth, which cannot be completely avoided, but can be reduced by choosing the parameters of the grinding wheel at a given angle Σ.

The calculated error of the milling tooth profile, according to I.S. Lazebnik, is determined by errors that arise as a result of approximate profiling and backing of the milling tooth [9]. The calculated error of the milling cutter tooth profile f_Σ in the axial direction and $f_{\Sigma n}$. The normals are determined from the expressions:

$$f_\Sigma = \Delta f - f, \quad f_{\Sigma n} = \Delta f_n - f_n \tag{3}$$

where Δf- the organic error measured in the axial direction; Δf_n and f_n- OP and deviation of the tooth profile from the straight line caused by occlusion, measured according to the normal.

Let's set the task of determining the error of the profile of a milling cutter with a front angle not equal to zero ($\gamma_B \neq 0$).

The planes A-A, B-B and C-C intersect the axis of the milling cutter and the intersection points of the circle with a diameter of dm0 with the front surface, respectively, for the new non-threaded milling cutter, in the design section and for the fully re-threaded milling cutter (fig.1). Let's denote the angles between the planes of sections by φ_1 and φ_2.

For a non-overfilled milling cutter, the radii of the circles of the protrusions of the depressions are greater than the corresponding radii in the calculated section by an amount:

$$\Delta_{r_1} = \frac{K_{z_0}\varphi_1}{2\pi} \tag{4}$$

For fully reworked cutters, the specified radii are respectively equal:

$$\Delta_{r_2} = \frac{K_{z_0}\varphi_2}{2\pi} \tag{5}$$

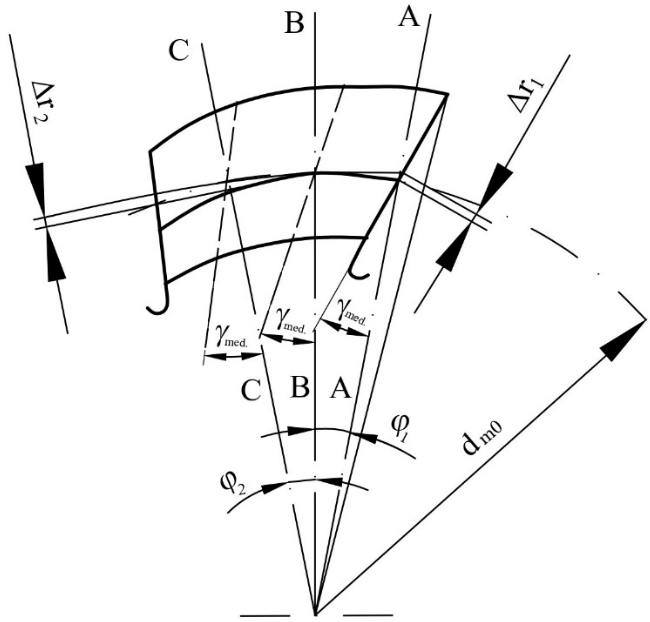

Fig.1. The scheme for determining the error of the tooth profile of the milling cutter with $\gamma_6 \neq 0$

The plane of the section B-B is symmetrical with respect to the planes A-A and B-B, thus the

$$\Delta_{r_1} = \Delta_{r_2} = \frac{K_{z_0}\varphi}{2\pi} \qquad (6)$$

angles $\varphi_1 = \varphi_2 = \varphi$ and.

With overflows of error Δf_n, f_n and accordingly $f_{\Sigma n}$ they may change. Obviously, all other things being equal, the change in error $f_{\Sigma n}$ with overflows, the greater the value, the more K, z_0 and φ.

Many elements of the technological system have an impact on the accuracy of dental treatment. The article discusses the nature and classification of gear processing errors, as well as their impact on the accuracy of the gear being processed. A table of the influence of errors in the technological system on the main parameters of the producing surface of the tool is presented.

The accuracy of gear processing of cylindrical gears, as well as the accuracy of mechanical processing in general, is influenced by the following main factors [10]:

1. The accuracy of manufacturing the elements of the technological system (TS) — machine tool, attachment, tool, workpiece.
2. The accuracy of the machine settings and the installation of tools and workpieces.
3. Elastic deformations of TC elements due to instability of cutting forces and non-rigidity of these elements.
4. Wear, thermal deformations of vehicle elements during processing, redistribution of internal stresses in the workpiece during various operations, etc.

The geometric, kinematic and dynamic components of machine precision are distinguished. The geometric accuracy of the machine is determined by the accuracy of the dimensions, shape and relative position of the machine elements in a static state. The kinematic and dynamic accuracy of the machine is manifested during its operation. The first is determined by the accuracy of the mutual superposition of all elements of the vehicle during the entire processing time of the part, the second by fluctuations in the values of the kinematic accuracy of the machine due to the non—rigidity of its elements and periodic changes in the forces acting on them. The kinematic and dynamic accuracy of the machine has a particularly great influence on the accuracy of tooth processing when processing teeth using the rolling method.

The accuracy of the shape, dimensions and location of the lateral surfaces of the teeth is determined by the accuracy and constancy of the mutual positions of the producing contour and the product at each moment of time. The errors in the relative position of each conjugate point of the producing and processed contours consist of: a) errors in the relative position of the tool and the workpiece in space created by inaccuracies in the manufacture and configuration of the machine and tooling, as well as inaccurate running-in movements; b) errors in the profile of the producing contour (tool) itself.

The kinematic accuracy of the machine does not matter in machines operating using the free-rolling method (gear shaving, tooth-honing, tooth-rolling, tooth-grinding, etc.), since the running-in movement on these machines occurs as a result of direct engagement of the tool and the product.

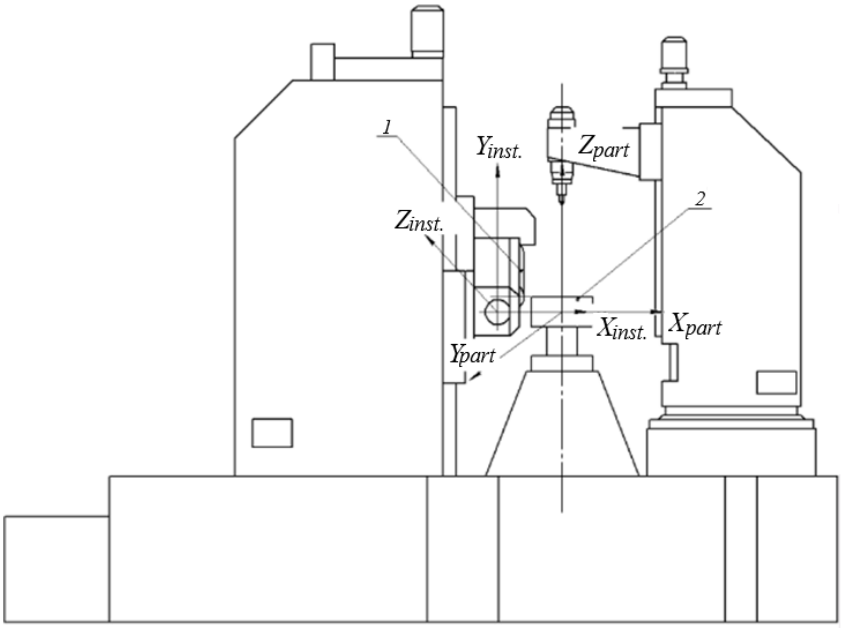

Fig.2 Technological system of the gear milling machine: 1- hob gear cutter, 2-gear

In the manufacture of gears according to the method of copying the profile, the errors of the tool itself and the basing of the tool and the preparation on the machine, the geometric accuracy and rigidity of the machine are of paramount importance. In the manufacture of gears by the rolling method, the importance of the kinematic and dynamic accuracy of the machine increases.

The nature and classification of dental processing errors

All the processes of shaping and finishing the teeth of cylindrical gears are intermittent and periodic due to the intermittent location of the teeth of the wheel on its crown, the limited number of teeth of the tool, the nature of the interaction of the wheel and the tool during tooth processing. Sinusoidally varying gear working errors also occur due to the reasons of harmonic errors of rotating elements of the vehicle, the gear working machine (gears, shafts, blanks, tools, etc.) and errors of the teeth of the workpiece that occurred during previous operations.

Practice shows [10] that in real gears, a limited number of harmonic vibrations are noticeably manifested, caused by: a) wheel installation errors during tooth formation; b) the beating of the dividing wheel in the gear machine; c) the beating of the worm of the dividing transmission of the machine; d) the beating of the gear cutting tool; e) the axial beating of the lead screw.

These inaccuracies are found accordingly: a) by the radial runout of the gear ring; b) by the accumulated error of the circumferential pitch measured from the base during gear processing; c) by the longitudinal stripes observed on the bevel-toothed wheels, or cyclic errors of the corresponding frequency; d) by sinusoidally varying profile errors; e) by the undulation of the lateral surface of the teeth of the bevel-toothed wheels.

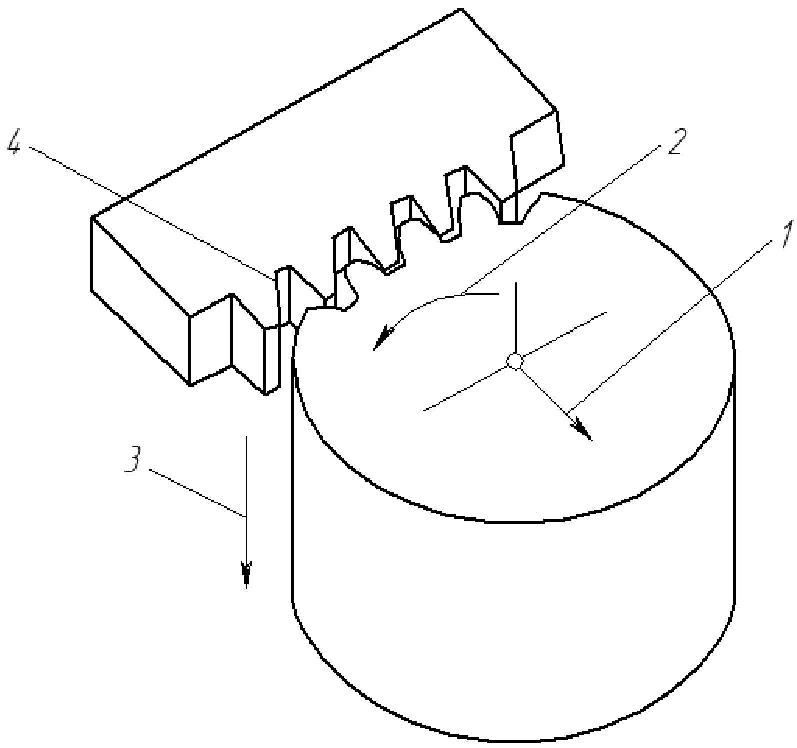

Fig. 3 Four types of errors in dental treatment: 1- radial, tangential, axial, producing surface

Other periodic errors [11] have little effect under normal conditions and appear only when their values significantly exceed the technically permissible norms. The effect of all random errors, which do not have a periodic nature of change, is one percent of the total error of the wheel and can be considered separately with sufficient accuracy.

The periods of fluctuations of the components of the periodic error of the wheel are interconnected by the ratio:

$$T_1 = 2T_2 = 3T_3 = ... = iT_i \quad (7)$$

where T_1 - the period of the main oscillation is equal to 2πn; n - the number of revolutions of the wheel during gear cutting; T_2, T_3, …, T_i - the periods of the components of the wheel error.

Consideration of wheel errors in the form of a periodic function allows a new approach to solving a number of practical problems. The most significant of them are: finding product errors based on particular sinusoidal vibrations acting during the manufacture of gears; finding the correct methods for measuring the total periodic error of the wheel and decomposing it into a number of separate harmonic components during technological analysis to determine the period, amplitude and initial phase in order to detect the primary sources of the total periodic error of the wheel; finding links between periodic error and its manifestation during operation of this gear in transmission in the form of noise, vibrations, dynamic loads.

The effect of individual errors that occur during gear processing can be reduced to four types

(Fig. 3): a) a change in the radial distance between the tool and the gear being processed — radial machining errors; b) a violation of the rolling of the tool and the product or inaccuracies of division — tangential machining errors; c) errors in tool movement along the axis of the product — axial processing errors; d) deviations of the producing surface of the tooth working tool — errors of the producing surface.

Radial error tooth treatments occur due to errors in the basing of the product on the machine, the radial runout of the tool and periodic fluctuations in the position of the spindle of the product (table swing) or the tool. Radial machining errors are characterized by the fact that they remain constant in any axial section of the wheel. Many examples can be given of the causes of errors in the basing of the workpiece on the machine: the beating of the centers of the machine relative to the axis of rotation of the table, the beating of the center sockets of the workpiece relative to its mounting necks, the beating of the mandrel of the machine table relative to the axis of rotation, the beating of the part due to the gap when it is placed on the mandrel, the separation of the technological and installation base, for example, during alignment workpieces on the machine according to its outer diameter.

Similar reasons cause radial runout of the tool: runout of the tool spindle seats, runout of the mandrel under the tool, gap of the tool landing on the neck or mandrel, tool manufacturing error.

Tangential error [11, 12, 13] tooth processing occurs mainly due to a violation of the rolling of the tool and product in machines operating by the rolling method, or due to division errors in machines with a dividing mechanism. The sources of these errors are errors in the links of the kinematic chain of machine tools and mainly the final worm pairs or dividing discs of machine tools and lead screws that are included in the rolling chain. The tangential processing errors remain constant along each contact line.

The axial error of the gear processing occurs mainly due to inaccuracies in the machine guides, the misalignment of the workpiece axis, and in some cases due to errors in the kinematic chain of the machine. The axial machining errors remain unchanged in each end section of the wheel. These errors cause a violation of the longitudinal contact, and in skew-toothed wheels, the high-altitude contact of the teeth.

Errors in the producing surface of the tool arise due to the use of approximate methods of profiling the tool [9] or errors in its manufacture and sharpening. In addition to these errors, wheel inaccuracies related to the influence of the intermittency of the cutting process due to the feed and the finiteness of the number of cutting edges of the tool should also be included here [14]. Any deviation of the shape of the producing surface of the tool from the exact surface creates a profile error on the product, and when cutting bevel wheels, also an error of the contact line. Inaccuracies in the profile angle of the producing surface of the tool also cause deviations in the engagement pitch and direction of the contact line on the product, which leads to non-smooth operation of the straight-toothed wheels and a violation of the high-altitude contact of any wheels.

The influence of errors in the technological system on the main parameters of the tool's producing surface is shown in Table 1.

Table 1. The influence of errors in the technological system on the main parameters of the producing surface of the tool

Errors of the technological system		The angle of intersection between the axes of the tool and the product, in °	The parameter of the screw surface of the product	The center-to-center distance between the tool and the workpiece, in mm
		ε	P	A_w
Radial errors	Errors in the installation of the workpiece	+	-	+
Radial errors	Tool installation errors:	+	-	+
Tangential errors	- misalignment of the milling cutter axis;	-	+	-
Tangential errors	- radial runout of the cutter.	-	+	-
Tangential errors	Kinematic error of the dividing wheel	-	+	+
Tangential errors	The periodic error of the dividing wheel	-	+	+
Tangential errors	Kinematic and geometric eccentricity of the workpiece	-	+	-
Axial errors	Periodic error (swing) the table	+	-	+
Axial errors	Cyclic errors of the worm and the dividing gear wheel of the machine	+	-	+
Axial errors	The inclination of the guides of the tool carriage in the longitudinal plane	+	+	+
Axial errors	Tilt of the table guides in the longitudinal plane	+	+	+
Axial errors	The inclination of the guides of the tool carriage in the transverse plane	+	-	+
Axial errors	Tilt of the table guides in the transverse plane	-	+	-
Axial errors	The end runout of the base end of the workpiece	-	+	-
Errors of the producing surface of the tool	Inaccuracies inherent in the slicing method			
Errors of the producing surface of the tool	Inaccuracy of the milling cutter tooth profile	-	+	-
Errors of the producing surface of the tool	The number of cutting edges of the cutter	-	+	-
Errors of the producing surface of the tool	Changing the shape of the cutting edges of the cutters as a result of their wear	-	+	-
Errors of the producing surface of the tool	Inaccuracy in the manufacture or reworking of the tool			
Errors of the producing surface of the tool	Inaccuracy of the milling cutter's producing profile (PP)	-	+	-
Errors of the producing surface of the tool	Deviation of the front surface of the milling cutter tooth	-	+	-
Errors of the producing surface of the tool	The error of the helical line and the steps of the mill rails	-	+	-
Errors of the producing surface of the tool	Single tool pitch errors (corresponding to local shear of the cutting edge)	-	+	-
Errors of the producing surface of the tool	Inaccuracy of the inclination or pitch of the screw chip grooves of the tool	-	+	-
Errors of the producing surface of the tool	The error of the cutter installation			
Errors of the producing surface of the tool	The runout of the main cylinder in the manufacture of a milling cutter relative to the control collars	-	+	+
Errors of the producing surface of the tool	The runout of the mandrel of the gear cutting machine relative to the axis of rotation	+	+	+
Errors of the producing surface of the tool	Non-concentricity of the hole in the mill and the mandrel of the machine	+	+	+

Conclusions.

The considered method makes it possible to construct with sufficient accuracy a three-dimensional model of the interaction of three elements of the technological system: a machine tool - a worm gear cutter- a workpiece. The technique allows us to take into account the relationship and the vector direction of the errors that occur.

The influence of errors in the technological cutting system on the calculated parameters of the producing surface of the tool has been established.

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