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COMPUTATION OF SHAPING ERRORS FOR FINE BORING OF SMOOTH AND STEPPED HOLES

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Abstract. On the basis of precision theory we propose the method of computation of static and dynamic errors of cross-sectional shapes of holes in fine boring of smooth and stepped holes. We consider particular cross-sectional shape errors caused by such factors:

– Error of the tooled hole form caused by the axis hope displacement in the workpiece relative to the spindle axis;

– Error of the tooled hole form caused by the hole out-of-roundness in the workpiece;

– Error of the tooled hole form caused by unevenness of the cutter radial compliance at the angle of spindle rotation.

According to time characteristics the errors can be divided into static with frequency substantially less than the lowest natural frequency of the process system, and dynamic, caused by vibrations. Static error rate is usually a multiple of the spindle speed.

The computations of deviations from the roundness of the cross section caused by vibrations are determined by computing the amplitudes of forced vibrations. Computations of individual static errors based on the average values of compliance, the material being processed and the processing mode are reduced to construction of nomographs for various materials.

Dynamic errors are determined by computation of forced vibrations amplitudes on the basis of systems of ordinary differential equations describing the vibrations of a machine closed dynamic system. These equations allow to compute the amplitude of the forced vibrations of smooth and stepped boring bars. A distinctive feature of the computations for multiple tooling is allowance for mutual influence of excitations arising at each step of a boring bar.

It is assumed that at multiple tooling each of the working cutters creates its own errors, the values of which are found by the nomograms for single-cutter tooling. Full tooling error at each step caused by some source of error is determined as the sum of the errors: of both, own and additional, caused by all working cutters. Additional errors can be found through coefficients of influence through dividing by the respective cutter's own compliance and through multiplying by the appropriate factor of influence.

We obtained results of computations and experiments of the dependence of the total error on the ratio of the boring bar steps lengths.

Analysis of roundness charts of the bored holes shows that vibrations can be a factor largely determining the shape of the cross section of the hole.

Experiments have shown that when the rotation speed changed the excitations of the spindle poles changed too. Under unfavorable excitation frequencies the tooling errors increase by 1,5–2 times.

The study results allow us to compare the two most common ways to reduce the errors caused by elastic deformations: the use of the dynamic damper and the processing of holes in two runs.

The experimental results confirm the non-monotonic dependence of the amplitudes of forced vibrations on the ratio of the boring bar steps lengths.

Introduction

Improving the precision in mechanical engineering is of great technical and economic importance, since the manufacturing and assembly precision has the determining influence on the quality of the machines, their reliability and durability. A prominent place in the engineering industry is taken by the task of improving the final hole machining precision - the operation, for which the use of fine boring machine (FBM) is very effective in the mass production.

Problem statement. Analysis of modern information sources on the subject of the article.

The impact on the precision of the overall FBM layout solutions was studied by a number of scientists [1, 2], who developed recommendations for the design of the bearing systems of machines, for the hydraulic drive and others. Implementation of these recommendations has led to an increase in the precision of machine tools and brought the problems of the spindle units quality to the forefront [3, 4]. The influence of the geometry and material of the tools and machining modes on the precision have been studied intensively by A. A. Matalina, S. N.Filonenko et al. [5, 6]. Using the communication parameters of the FBM dynamic quality and precision, providing development of standards for idling vibrations, unbalance and the use of diamond tools, as well as designing of the control equipment was implemented under the guidance of V.A. Kudinova, Yu. F. Kopeleva et al. [7, 8].

While noting the positive results of these studies one should pay attention to the lack of a uniform methodology for calculating the expected error of the hole forms processed on the FBMs. Thus, when designing of fine boring machine an engineer is unable to make grounded choices of several important design parameters. Although the achievable values of the FBM precision features in the standard test conditions are fairly completely set (processing of smooth cylindrical surface of the hard sample fixed in a very hard fixture by a short boring bar), it is still poorly known how the deviations from these conditions impact the precision. The influence of the size of a boring bar on the errors have not been fully established even for the processing of simple cylindrical holes. Thus it is especially difficult to predict the precision of widespread multiple tooling of stepped holes. Inadequate study of quantitative indicators of the interaction of concurrent spindles and elastic subsystems of tools and accessories makes the task of establishing the impact of these factors on the precision quite uncertain.

Precise holes are tooled at large indicators of stability reserve of the machine closed dynamic system, and therefore we can assume that there are no self-vibrations.

Statement of purpose of research

The objective is to develop a methodology for determining of tooling errors, generated by the static and dynamic deformations of the spindle unit with a boring bar in terms of boring of smooth and stepped holes.

Baseline

Analysis of the FBM precision indicates that the deviations from roundness ΔR of the cross section of a tooled hole can be determined by summing the initial error ΔR_i, obtained by machine tests in the normalized conditions (tooling of a continuous hole in hard sample) and the error by a short rigid boring bar ΔR_{elast}, determined by elastic deformations, which are formed by increasing compliance compared to the standard test conditions.

The initial error ΔR_i was investigated during the test of spindle units [3], which were installed in the middle of the FBM bridge and equipped with a rigid boring bar ($d_1 = 27\,mm,\ l_1 = 36\,mm$). In the steel and bronze samples in a rigid fixture, holes with a diameter of 34 *mm* were bored at $n = 3000\,rpm,\ t = 0{,}1\,mm,$ $s = 0{,}03\,mm/rev$.

With increasing of compliance K_u of instrument subsystem processing errors increase, and when $K_u = 0{,}1...0{,}15\,\mu m/N$ the errors ΔR_{elast} become comparable with ΔR_i.

Assessing the impact of vibrational interactions in a closed dynamic system of a machine on the machining precision, researchers distinguish static and dynamic components of tooling errors. The static errors in fine boring have a frequency less than the lowest natural frequency of the system and is usually a multiple of the spindle speed. Typically static errors form out-of-roundness of a hole. The machine vibrations are the determining factors of the dynamic errors. Studying the effect of vibrations on the precision, it should be noted that analysis of bore roundness charts indicates that the vibrations may be the main factor in determining the error of a cross-sectional shape.

Paper [9] has developed the method of computation of the following individual static cross-section errors:

– Π_k – diametric precision of the shape of a processed hole, caused by the error $2\Delta K$ of system radial compliance in the tool:

$$\Pi_k = 2\left(K_{\max} P_y - K_{\min} P_y\right), \tag{1}$$

where P_y is the radial cutting force; $K_{\min}, K_{\max}$ – the minimum and maximum spindle compliance of the angle of rotation;

– Π_o – the diametric error of the form of a processed hole, caused by the out-of-roundness of holes in the workpiece:

$$\Pi_o = 2 \cdot K\left[P_y(t) - P_y(t - H_o)\right], \tag{2}$$

where H_o is the greatest difference between the radii of the hole in the workpiece (out-of-roundness);

– Π_e – the diametric error of the form of the processed hole, caused by the displacement of hole axis in the workpiece relative to the spindle axis:

$$\Pi_e = 2 \cdot K \cdot P_y(t) - K\left[P_y(t+e) + P_y(t-e)\right], \tag{3}$$

where K – is the radial system compliance of the tool; e – eccentricity.

Errors Π_o and Π_e are formed under conditions of variable slice thickness. Estimates of the impact of uneven allowance for deviations from hole circularity cause values of ΔR in the range of 0.01 - 0.2 microns. The experimental data allow the same order of magnitude.

Full static deviation from circularity is expressed through individual errors $\Delta R_{st} = 0,5 \cdot \sqrt{\Pi_e^2 + \Pi_o^2 + \Pi_\kappa^2}$. It is assumed that all individual errors are independent and normally distributed. Computations and measurements of individual static errors based on the average values of compliance, on the material being processed and the processing mode are reduced to the construction of nomograms to determine Π_κ, Π_o and Π_e. Fig. 1 shows the nomogram for steel. The nomograms for cast iron, bronze and aluminium have also been constructed and refined.

To determine the error in all cases we should assign cutting modes (s, t), determine the compliance of the spindle - boring bar system [10], as well as the values e/t, $2\Delta K/K$ and H_0/t. By connecting the values with the line segments on the nomogram S and K, and also values t with parameters e/t, or $2\Delta K/K$, or H_0/t we obtain the points on the intermediate axes I and II. By connecting the corresponding points on the axes I and II with segments, we find the points of intersection of the latter with the axis Π_i, according to the scale which defines the boring errors. Rules (keys) of use of the nomogram are shown in Fig. 1.

The characteristics of the variability of compliance $(2\Delta K/K)$, out-of-roundness (H_0/t) and the axis displacement (e/t) holes in the workpiece are combined on the right scale.

Deviations from the cross-sectional roundness caused by vibrations, are determined by vibrations amplitude “ A ”:

$$\Delta R_{dyn} = 2A.$$

The amplitude of the vibrations is determined on the basis of building of a computational model of a closed dynamic FBM system [11].

The equations of a closed dynamic system of a machine, allowing for the dynamic characteristics of the cutting process with the simultaneous operation of two cutters are presented in the form:

$$\begin{cases} m_0\ddot{y}_0 + b\dot{y}_0 + \dfrac{d_{22}}{d}y_0 - \dfrac{d_{02}}{d}y_2 = P_0\sin wt + \dfrac{d_{01}\cdot d_{22} - d_{02}\cdot d_{12}}{d}P_{z1}; \\ m\ddot{y}_2 + \dfrac{d_{00}}{d}y_2 + \dfrac{d_{02}}{d}y_0 = P_{z2} + \dfrac{d_{00}\cdot d_{12} - d_{01}\cdot d_{02}}{d}P_{z1}; \\ T_p\dot{P}_{z1} + P_{z1} = -K_{p1}y_2\dfrac{d_{12}}{d_{22}}; \\ T_p\dot{P}_{z2} + P_{z2} = -K_{p2}y_2, \end{cases} \tag{4}$$

$$d = d_{00}\cdot d_{22} - d_{02}^2,$$

$$m = m_{br} = 0,243\cdot\left[m_1\frac{l_1^3}{l^3} + m_2\right],$$

where y_0 – vibrating mass movement m_0; $\ddot{y}, \dot{y}$ – the first and the second time derivatives; P_{z1}, P_{z2} – cutting forces on appropriate cutters; T_p – inertial constant of chip formation; K_{p1}, K_{p2} – cutting factors of relevant cutters; d_{iK} – coefficients of influence defined by the Vereshchagin rule with allowance to angular movements; m_0 – inertial spindle characteristic given by weight brought to the cross section of a flange; m_{br} – inertial characteristics of the boring bar, given by the weight brought to the cross section of the second cutter.

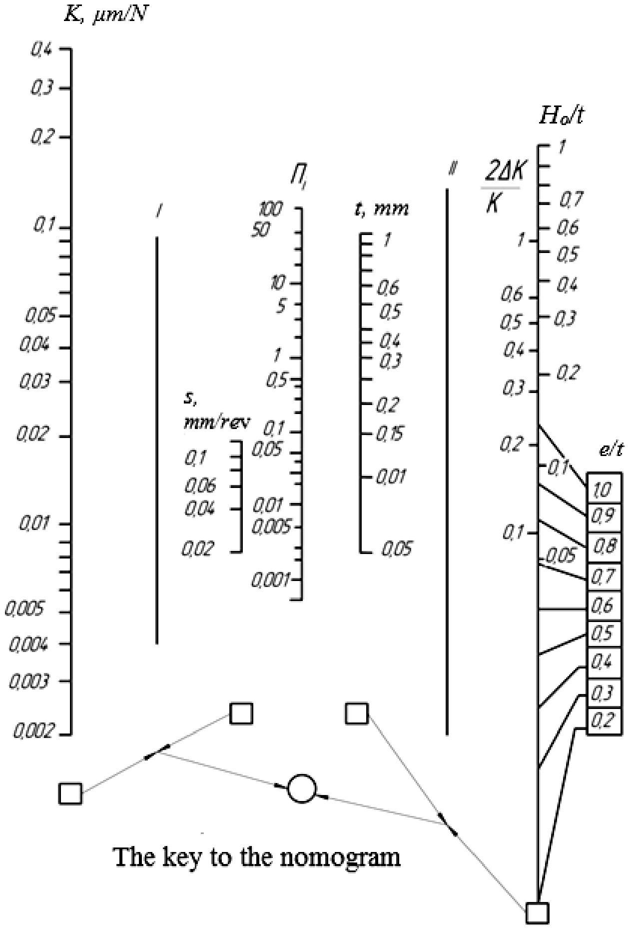

Fig. 1. *Determination of static errors in the boring of samples (steel 35) according to the nomogram:* O *– values of the individual errors* $П_i$; K *– the elastic system compliance;* S *– feed per revolution;* t *– cutting depth*

Full elastic error can be determined by summing the static and dynamic errors:

$$\Delta R_{elast} = \Delta R_{st} + \Delta R_{dyn} . \tag{5}$$

By presenting the processed deviation from the roundness of the holes $\Delta R = \sqrt{\Delta R_i^2 + \Delta R_{elast}^2}$ one can use the above ratios to assess the effectiveness of various ways to improve the machining precision. Reduction of ΔR_u can be achieved by increasing the precision of the bearings and by the use of special techniques of assembly of duplexed supports. In [12]. We proposed the method of selective matching of angular contact bearings in duplex couples containing bearings with the same beats magnitude and with mutually perpendicular installation of large out-of-roundness axes. In this case the dynamic quality of spindle units is increased, and the bore shape error is reduced to 0.5–0.6 microns.

It is found that 1/5 of all FBM tooled bores have stepped forms. The stepped boring bars fitted with vibration dampers for large sweeps are used in these cases to improve the performance and precision. To calculate the errors that occur in a fine multiple boring bar tooling, we retain a common approach to the definition of individual errors and methods of their summation, given above. The allowance for mutual influence of excitations arising at each step of the boring bar is the distinctive feature of the computations for multiple tooling.

Moving d_{iK}^{lin} shall be found by using the formulas drawn up with the Vereshchagin method.

The above method of computing the static errors for single tooling is based on the summation of individual errors, caused by the displacement of the workpiece axes and of the spindle (Π_e), by out-of-roundness on the hole in the workpiece (Π_o) and by uneven compliance of the spindle assembly on the angle of rotation (Π_K).

For multiple tooling we assume that each j-th of n working cutters makes its own errors Π_{ej}, Π_{oj} and Π_{Kj}, the values of which are found by the nomograms for single cutter tooling. Uneven compliance of the spindle for its rotation angle, characterized by, for example, an ellipse, will lead to errors in each of the steps in the form of ellipses whose axes lie in one plane. The total error of processing on each of the steps (or otherwise, for each tool number) caused by this source of error, shall be found as the sum of the errors: of both, own and additional, caused by all working cutters.

Additional errors can be found through coefficients of influence by dividing by its own compliance with the respective tool ($K_j = d_{jj}$) and by multiplying by the appropriate factor of influence. For example, in a two-cutter tooling of a two-stepped hole the error of the second cutter is equal (most remote from the flange):

$$\Pi_{K1} \cdot \frac{d_{12}}{d_{11}} + \Pi_{K2} \cdot \frac{d_{22}}{d_{22}} .$$

In summary, for the i-th cutter the error from uneven compliance is:

$$\sum_{j=1}^{n} \Pi_{Kj} \cdot \frac{d_{ji}}{d_{jj}} .$$

Full deviation from the roundness of the cross-sectional shape, determined for i-th cutter by influence of static errors, can be found as:

$$\Delta R_{ci} = 0,5 \sqrt{\left[\sum_{j=1}^{n} \Pi_{ej} \cdot \frac{d_{ji}}{d_{jj}} \right]^2 + \left[\sum_{j=1}^{n} \Pi_{Kj} \cdot \frac{d_{ji}}{d_{jj}} \right]^2 + \left[\sum_{j=1}^{n} \Pi_{oj} \cdot \frac{d_{ji}}{d_{jj}} \right]^2} . \tag{6}$$

Dynamic errors for the fine boring are determined by the computation of forced vibrations [11, 7].

Fig. 2 shows the dependence ΔR_{elast} on the ratio of the step lengths of a two-stepped boring bar. We compared the values ΔR_{elast}, obtained by computation and experiment. The difference between them is no more than 15 %. In this experiment one could see that the dynamic components of a deviation from the roundness are substantially larger than the static components. These dependences reflect the fact that during tooling of the stepped holes the minimum errors are formed at the ratio of the step lengths that are inappropriate for maximum rigidity of the boring bar.

The developed computation method is an elaboration of the general theory of machining precision. The proposed methodology clarifies and develops the general concepts and methods for the precision determination of the cross-section shape of the hole, tooled by the fine boring machine. The obtained results relate to determination of processing errors generated by the static and dynamic deformations of the spindle and boring bar assembly under high stringency of a tooled workpiece and the device in which it is installed.

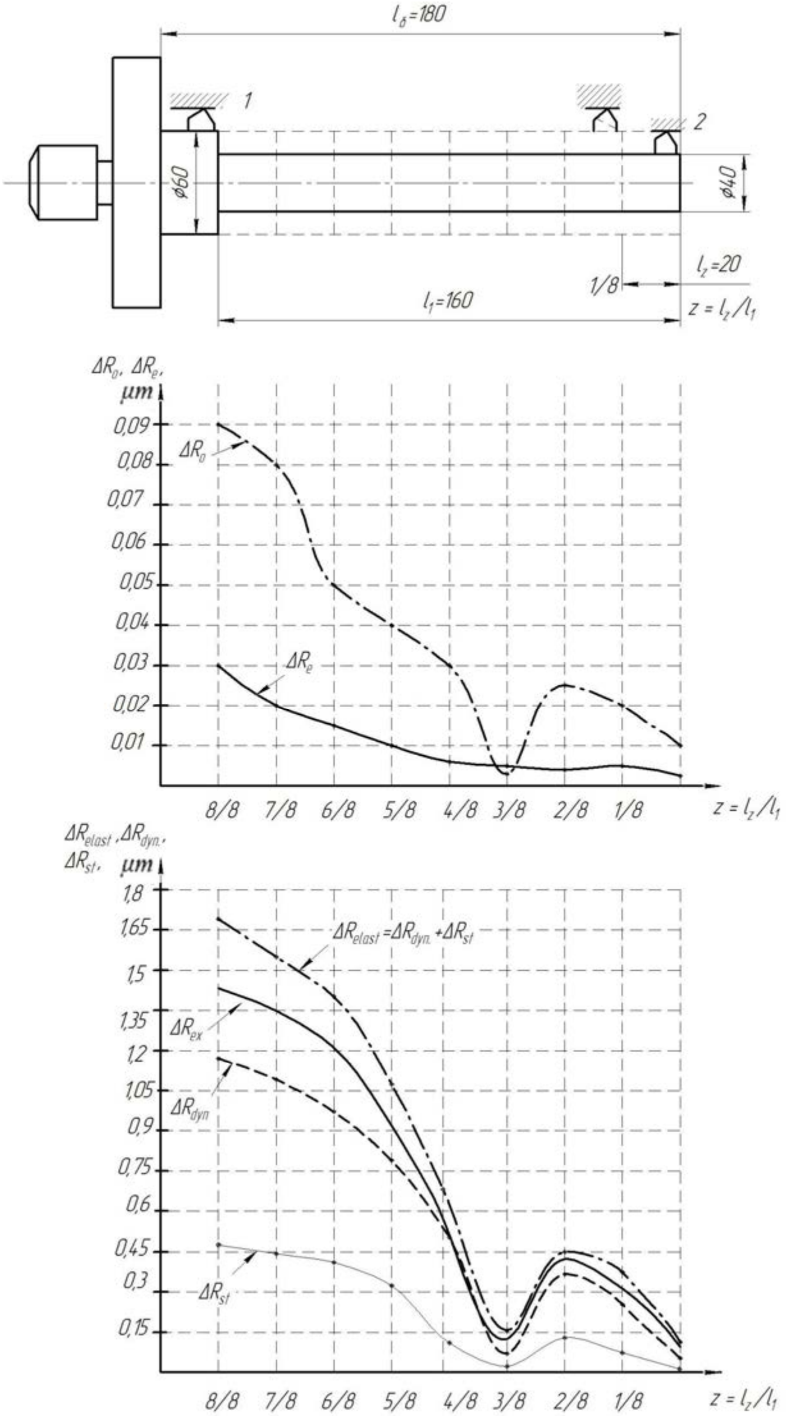

Fig. 2. *The dependence of the static and dynamic errors on the ratio of the lengths of two-stepped boring bar*
(Steel 35 $t = 0,2\,mm, s = 0,05\,mm\,/\,rev, v = 3,3\,m\,/\,c$ *)*

Studies [13] of excitations in the spindle poles during speed changes show that the transition from unfavourable to favourable speed leads to an increase in ΔR about 1,5–2 times Fig. 3.

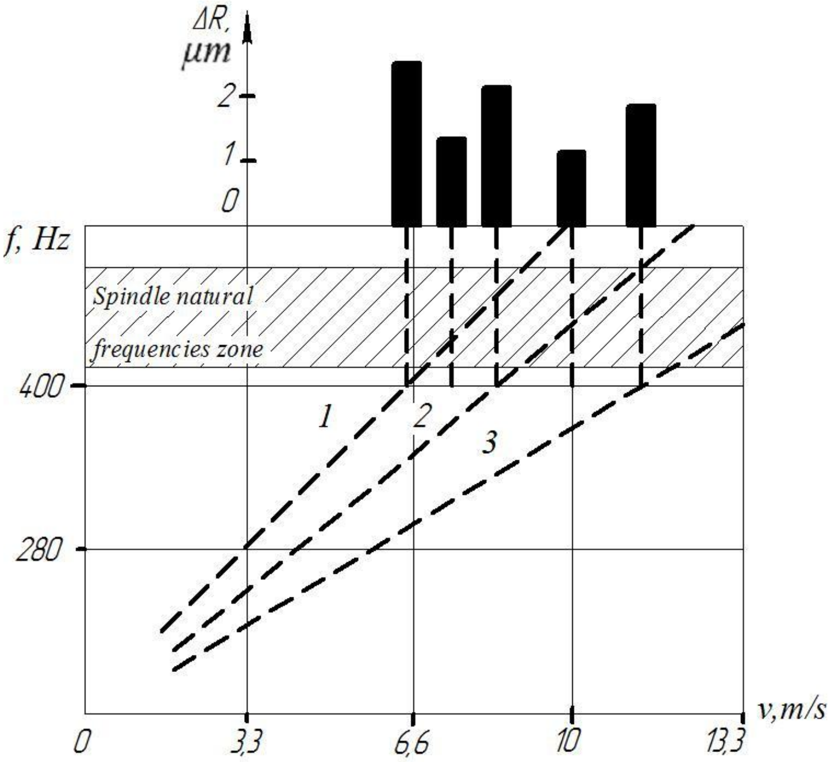

Fig. 3. *Dependencies of deviations from roundness when you change the frequency of the idle rotation of the spindle 1, 2, 3 – harmonics of vibration excitation caused by the ball-bearings at idle rotation*

Analysis of the calculated and experimental data allows you to compare two of the most common ways to reduce errors caused by elastic deformations: the use of dynamic damper and tooling of the holes by two runs.

The dynamic component of the deviations from roundness is reduced when using the dynamic vibration damper, and the static component is decreased when processing the holes in two runs. When tooling the holes in one pass the precision of the sectional shape is substantially affected by out-of-roundness of the holes in the workpiece. For boring bars with diameter from 50 to 100 mm, with the length to diameter ratio l/d ranging from 1 to 4, and depth of cut from 0,03 to 0,4 mm in average we observe such ratio between individual static errors $\Pi_K : \Pi_o : \Pi_e = 40:100:10$. This ratio is changed after the second passage by reducing of Π_o, and the average ratio is performed when $\Pi_K : \Pi_o : \Pi_e = 100:30:5$, i.e. the variability of compliance becomes the determining factor. It should be noted that the use of the dynamic damper provides improved precision under any tooling conditions. Proper configuration of the dynamic dampers can reduce the dynamic component of the shape error by 4–5 times.

Initial data for the computation is:

– the tool system compliance;

– the processed material;

– processing mode (t, s);

– the out-of-roundness of a hole in the workpiece (2 H_0);

– the hole axis displacement in the workpiece relative to the spindle axis (e);

– the difference between the minimum and maximum compliances ($2\Delta K$) during rotation of the spindle;

– elastic characteristics of the spindle unit;

– the size of the boring bar;

– vibrational spectra as a function of the idle spindle speed, containing data on the kinematic error of spindle rotation and dynamic excitations.

It is clear that the comparison of the results of computations and experiments can be carried out strictly enough if the experiment recorded the conditions across all indicators mentioned above. The results of the individual experiments can be affected also by the combination of further conditions, for example, the mutual orientation of the shaft in the workpiece and stiffness ellipse of an elastic system or the hole axis displacement direction in the workpiece relative to the stiffness axes.

The dependence of the deviations on roundness at changing of compliance is manifested when the kinematic error of the spindle unit is quite small. The table shows the computational dataand the results of the experiment carried out during the tooling of steel. This reveals a good agreement after we deduct from the experimental values of out-of-roundness the value of ΔR_o obtained by extrapolating the relation of $\Delta R(K)$ to the value $K = 0$, in which ΔR is mainly determined by the kinematic error of the spindle unit.

Table

The dependence of the roundness deviations while changing compliance

K, *μm/kg*	Computation ΔR_o, *μm*	Experiment	
		ΔR, *μm*	$\Delta R - \overline{\Delta R_o}$, *μm*
0,45	0,44	1,2	0,45
0,65	0,6	1,4	0,65
1,25	1,26	1,9	1,15

Conclusions

1. There have been developed the method of computing the precision of a cross-sectional shape and of a hole roughness, tooled by FBM. There have been studied the static and dynamic errors in fine boring of smooth and stepped holes.

2. There have been constructed nomograms to calculate the static errors caused by eccentricity of the installation, by out-of-roundness of the hole in the workpiece, as well as by non-uniformity of stiffness for angle of rotation.

3. Dynamic errors are defined on the basis of computation of the amplitudes of forced vibrations in boring of two-stepped holes.

4. The dependences of the amplitude of forced vibrations and deviations from the roundness of a bored hole on the ratio of the cantilevered boring bar step lengths are non-monotonic; and the minimum amplitude of the vibrations when tooled by the outermost cutter from the boring bar flange, as well when working with two simultaneously operating cutting edges is realized when the ratio of the lengths of the steps is inappropriate to maximum rigidity.

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