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Full-factor matrix model of accuracy of dimensions performed on multi-purpose CNC machines

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ABSTRACT

Introduction. One of the main reasons that modern multi-purpose CNC machines do not use the capabilities of multi-tool processing is the lack of recommendations for design in this direction and, accordingly, for adjustment schemes. The study of the possibilities of multi-tool processing on multi-purpose machines is the subject of the work. **The purpose of research:** The problem of developing full-factor matrix models of dimensional accuracy and its sensitivity to the machining process is considered to increase the machining efficiency while ensuring machining accuracy using the technological capabilities of multi-tool machining on modern multi-purpose CNC machines. For this purpose, full-factor matrix models of the size scattering fields performed on multi-tool double-carriage adjustments have been developed, taking into account the cases of processing parts with dimensions that differ sharply in different directions, which are often encountered in practice, and in this case, the significant influence of the turns of the workpiece on the processing error, especially in directions with sharply different overall dimensions. **Results of research:** The developed accuracy models make it possible to calculate not only plane-parallel displacements of the technological system for double-carriage adjustments, but also angular displacements around base points, take into account the combined effect of many factors – a complex characteristic of the subsystems of the technological system (plane-parallel matrix of compliance and angular matrix of compliance), the geometry of the cutting tool , the amount of bluntness of the tool, cutting conditions, etc. As a result, based on the developed accuracy models, it is possible to obtain several ways to control multi-tool machining, including improving the structure of multi-tool adjustments, calculating the limiting values of cutting conditions. Based on the developed full-factor matrix models, it became possible to develop recommendations for the design of adjustments and the creation of an automated design system for multi-tool machining for a group of modern multi-purpose CNC lathes. **Scope of the results:** The results obtained can be used to create mathematical support for the design of operations in CAD-systems provided for multi-tool multi-carriage machining performed on multi-purpose machines. **Conclusions:** The developed models and methodology for simulating the machining accuracy make it possible to increase the accuracy and efficiency of simultaneous machining, to predict the machining accuracy within the specified conditions.

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Introduction

The high cost of modern machine tools with numerical control (CNC) in the world market dictates the need to use the technological capabilities of these machines at a high level. Here, not only the reduction in processing time is of great importance, but even the minimization of auxiliary times. One of the ways to improve the productivity of machining on CNC machines is to take advantage of the multitool machining capabilities of these machines.

Multi-tool machining is an integral part of machine building. Multi-tool adjustments, which have great potential for concentration of transitions, make it possible to perform all the shaping technological

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transformations of multi-product parts in one automatic turning operation before heat treatment, even in most cases it performs all machining, from the workpiece to the finished part. The range of lathes working with multi-tool adjustments is quite wide. However, the analysis of the level of use of the capabilities of multi-tool machining on multi-purpose CNC machines, carried out in factories, showed that adjustments with parallel multi-tool machining are little used. [5, 7, 10–12]. For this reason, an increase in the efficiency of using the technological capabilities of multi-tool machining on modern CNC machines is one of the problems in machine building that pushes for the solution.

The main prerequisite for solving the problem is the theory of multi-tool machining design, taking into account the capabilities of modern CNC machines. The theory of designing multi-tool machining on modern CNC machines is based on the balance of the mutual influence of the forces of the adjustment tools, taking into account the possibilities of tools movement along curved paths, as well as the arbitrary spatial arrangement of tools in the metalworking machine. For this reason, first of all, it is important to have models of machining errors that take into account the simultaneous influence of all components of the cutting forces of all setting tools in multi-tool adjustments with the spatial arrangement of tools and elastic displacements in all coordinate directions of the technological system. With this in mind, the matrix theory of multi-tool machining accuracy was created [6]. However, the generated machining error models take into account only the plane-parallel displacements of the subsystems of the technological system along the coordinate axes of the Cartesian coordinate system *XYZ* [5, 6, 12]. This approach to simulating the process of occurrence of machining errors for parts with overall dimensions of the same order in all coordinate directions is permissible. In practice, there are often cases of machining parts with overall dimensions that differ sharply in different directions. For example, long shafts (linear dimensions predominate), discs and flanges (diametric dimensions predominate). In these cases, the machining error is largely influenced by the rotations of the workpiece being machined, especially in directions with sharply differing overall dimensions, and for this it becomes necessary to create full-factor models of machining accuracy that also take into account angular displacements. Studies of other works [1–4, 13–26] show that in this area works are of a private nature and cover only some parameters. In these works, there are often experimental studies of multi-tool machining. But there is no information in any source about the mathematical simulation of the problem and, at the same time, the specification of multi-tool processing. The most important thing is that these models do not agree with the general laws of mechanics of elastically deformable systems, therefore it cannot be used to create a unified theory of machining accuracy that takes into account possible angular displacements of subsystems of a technological system.

In the industry, computer-aided design systems are used to design operations on modern multi-purpose CNC machines, but even here there are no possibilities to increase the machining accuracy and productivity of multi-tool machining by the method of numerical determination of feeds based on simulating the elastic displacements of the technological system, taking into account the limitations on dimensional accuracy and mutual influence of simultaneously working tools.

Also, on modern multi-purpose CNC machines, solving the problem of imposing technological transitions for double-carriage lathes in the available automated programming systems for operations is carried out in manual mode by trial and error. And this once again confirms the absence of a scientifically grounded methodology for the design of multi-tool multi-carriage machining on multi-purpose CNC machines and shows the need for its development.

Research methodology

The accuracy of the dimensions is the first requirement in the design, adjustment and implementation of the technological process. And therefore, the first task of parametrizing the designed technological process is the calculation of depths of cut and operating dimensions that make up a single section “Dimensional analysis of the technological process”. The second task of the parametrization stage is to calculate cutting conditions [8]. The dimensions carried out in multi-tool adjustments and intermediate depths of cut are directly related to the parameters of the cutting conditions. For this reason, these two tasks of parametrization of the technological process should be solved simultaneously [5, 6]. The basis of the matrix theory of multi-tool machining is formed by mathematical models of the accuracy of the dimensions performed by tools in multi-tool adjustments. Therefore, the modern level of mathematical models for the formation of dimensional errors in multi-tool adjustments is of particular interest.

As established in the science of machine building technology, the machining accuracy is determined by a whole complex of a number of random and regular factors, its mutual influence and mutual connection: elastic displacements of the technological system, dimensional wear of the cutting tool, geometric inaccuracy of the links of the technological system, temperature deformations, errors in the location of workpieces on the machine and errors in adjusting it to the size to be performed, scattering of depths of cut of workpieces and its physical and mechanical properties, etc. To a large extent, the machining accuracy is also influenced by the cutting conditions [8, 9].

The quantitative property of machining accuracy is the machining error. This machining error highlights the degree of inconsistency between the shapes and sizes of a real part and a given ideal scheme in the design.

All elementary components of the error can be conditionally divided into two groups [8]:

1. The elementary components of the error independent of the cutting conditions or weakly dependent on it (small): the error of the dimensional wear of the cutting tool (Δw), the geometric inaccuracy of the links of the technological system ($\sum\Delta f$), the error of temperature deformations ($\sum\Delta T$), the error of placement the workpieces on the machine (ε), the error in adjusting the workpiece to the dimension being performed (Δa);

2. An elementary component of the error, completely determined by the cutting conditions: the error of elastic displacements of the technological system (Δy).

Errors of the first group are of no interest during the development of simulation models defined for the design of a technological process. These components participate as constants in simulation models. Its meanings are taken from an extensive reference literature.

During the simulation of machining accuracy as a result of elastic displacements of the technological system from the influence of cutting forces, a special place is occupied by the elementary error Δy, which arises in the technological system. Its value is determined by cutting conditions, features of the technological system. For this reason, the elementary error Δy acts here as the main controlled object and its mathematical expression is required.

Due to the distortion of the performed size, in practice, another characteristic of machining accuracy is more in demand – the value of the scattering field of the performed size. Due to the mutual action of the force for multi-tool adjustments, two boundary cases have been established [5, 6]: opposite and non-opposite. In an opposite setup, all components of the cutting force of one carriage are directed against the corresponding components of the other carriage. Such adjustments are common for cam-operated turret lathes and multi-spindle automatic lathes. And in non-opposite adjustments, all the corresponding components of the cutting force of both carriages are directed in the same direction. On the modern group of CNC lathes, both adjustments are used equally.

Based on the foregoing, it can be noted that, in order to develop the theory of numerical design of multi-tool adjustments, complex models of distortion of the performed dimensions and its scattering fields are required, and these models should consider the structure of multi-tool adjustments – various types of cutters of the longitudinal or transverse carriage, the simultaneous operation of the longitudinal and transverse carriage.

The mechanism of the formation of the scattering field in double-carriage opposite adjustments is extremely complicated in comparison with one carriage machining [6]. The scattering of the strength properties of the workpiece material and the rigidity of the technological system determines the scale of the scattering interval of the size distortion $\overline{w_1}$ и $\overline{w_2}$. But the effect of changing the depth of cut on the carriages is ambiguous. Due to the fact that the cutting forces on the longitudinal and transverse slide are directed against each other, a change in depths of cut Δt_1 and Δt_2 can lead to a change in the balance of forces. As a result, the scattering intervals of the performed dimensions are of three different orders [6, 27]. By combining all 3 variants of the location of the scattering fields, it is possible to form a single model of the scattering field, taking into account not only the plane-parallel displacements of technological subsystems of the performed dimensions on the longitudinal carriage of double-carriage opposite adjustments, but also the angular displacements around the base points. Below is a full-factor matrix model of the performed diametrical dimension on the longitudinal carriage:

$$\Delta w_1 = \begin{cases}
\omega\left[e_{01} t_1 \overline{p_t^1} - e_0 t_2 \overline{p_t^2}\right] + \left[e_{01}\Delta t_1 \overline{p_{\Delta t}^1} + e_0 \Delta t_2 \overline{p_{\Delta t}^2}\right] + \omega\left[-\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right) t_1 \overline{p_t^1} + \right. \\
\left. + a^0_{O_0}\xi_0 a^0_{O_0} t_2 \overline{p_t^2}\right] + \left[-\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right)\Delta t_1 \overline{p_{\Delta t}^1} + a^0_{O_0}\xi_0 a^0_{O_0}\Delta t_2 \overline{p_{\Delta t}^2}\right] \\
\text{if } e_{01} t_1 \overline{p_t^1} - e_0 t_2 \overline{p_t^2} + \left(-\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right) t_1 \overline{p_t^1}\right) + a^0_{O_0}\xi_0 a^0_{O_0} t_2 \overline{p_t^2} \geq \\
\geq \dfrac{e_{01}\Delta t_1 \overline{p_{\Delta t}^1} + e_0 \Delta t_2 \overline{p_{\Delta t}^2}}{2} + \dfrac{\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right) t_1 \overline{p_t^1}\Big) + a^0_{O_0}\xi_0 a^0_{O_0}\Delta t_2 \overline{p_{\Delta t}^2}}{2}, \\
\text{where } e_{01} t_1 \overline{p_t^1} - e_0 t_2 \overline{p_t^2} + \left(-\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right) t_1 \overline{p_t^1}\right) + a^0_{O_0}\xi_0 a^0_{O_0} t_2 \overline{p_t^2} \succ 0; \\
\left(1 + \dfrac{\omega}{2}\right)\left[e_{01}\Delta t_1 \overline{p_{\Delta t}^1} + e_0 \Delta t_2 \overline{p_{\Delta t}^2}\right] + \left(1 + \dfrac{\omega}{2}\right)\left[\left(\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right)\Delta t_1 \overline{p_{\Delta t}^1}\right) + \right. \\
\left. + a^0_{O_0}\xi_0 a^0_{O_0}\Delta t_2 \overline{p_{\Delta t}^2}\right] \\
\text{if } -\dfrac{e_{01}\Delta t_1 \overline{p_{\Delta t}^1} + e_0 \Delta t_2 \overline{p_{\Delta t}^2}}{2} - \dfrac{\left(\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right)\Delta t_1 \overline{p_{\Delta t}^1}\right) + a^0_{O_0}\xi_0 a^0_{O_0}\Delta t_2 \overline{p_{\Delta t}^2}}{2} \prec \\
\prec e_{01} t_1 \overline{p_t^1} - e_0 t_2 \overline{p_t^2} + \left(-\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right) t_1 \overline{p_t^1}\right) + a^0_{O_0}\xi_0 a^0_{O_0} t_2 \overline{p_t^2} \prec \\
\dfrac{e_{01}\Delta t_1 \overline{p_{\Delta t}^1} + e_0 \Delta t_2 \overline{p_{\Delta t}^2}}{2} + \dfrac{\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right)\Delta t_1 \overline{p_{\Delta t}^1} + a^0_{O_0}\xi_0 a^0_{O_0}\Delta t_2 \overline{p_{\Delta t}^2}}{2}; \\
-\omega\left[e_{01} t_1 \overline{p_t^1} - e_0 t_2 \overline{p_t^2}\right] + \left[e_{01}\Delta t_1 \overline{p_{\Delta t}^1} + e_0 \Delta t_2 \overline{p_{\Delta t}^2}\right] - \omega\left[-\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right) t_1 \overline{p_t^1} + \right. \\
\left. + a^0_{O_0}\xi_0 a^0_{O_0} t_2 \overline{p_t^2}\right] + \left[-\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right)\Delta t_1 \overline{p_{\Delta t}^1} + a^0_{O_0}\xi_0 a^0_{O_0}\Delta t_2 \overline{p_{\Delta t}^2}\right] \\
\text{if } e_{01} t_1 \overline{p_t^1} - e_0 t_2 \overline{p_t^2} + \left(-\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right) t_1 \overline{p_t^1}\right) + a^0_{O_0}\xi_0 a^0_{O_0} t_2 \overline{p_t^2} \leq \\
\leq -\dfrac{e_{01}\Delta t_1 \overline{p_{\Delta t}^1} + e_0 \Delta t_2 \overline{p_{\Delta t}^2}}{2} - \dfrac{\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right)\Delta t_1 \overline{p_{\Delta t}^1} + a^0_{O_0}\xi_0 a^0_{O_0}\Delta t_2 \overline{p_{\Delta t}^2}}{2}, \\
\text{where } e_{01} t_1 \overline{p_t^1} - e_0 t_2 \overline{p_t^2} + \left(-\left(a^1_{O_1}\xi_1 a^1_{O_1} + a^0_{O_0}\xi_0 a^0_{O_0}\right) t_1 \overline{p_t^1}\right) + a^0_{O_0}\xi_0 a^0_{O_0} t_2 \overline{p_t^2} \prec 0;
\end{cases} \qquad (1)$$

$$\overline{p_t^1} = \begin{pmatrix} C_{P_x^1} t_1^{x_{P_x^1}-1} S_1^{y_{P_x^1}} \upsilon_1^{z_{P_x^1}} \\ C_{P_y^1} t_1^{x_{P_y^1}-1} S_1^{y_{P_y^1}} \upsilon_1^{z_{P_y^1}} \\ C_{P_z^1} t_1^{x_{P_z^1}-1} S_1^{y_{P_z^1}} \upsilon_1^{z_{P_z^1}} \end{pmatrix}; \qquad \overline{p_t^2} = \begin{pmatrix} C_{P_y} t_2^{x_{P_y^2}-1} S_2^{y_{P_y^2}} \upsilon_2^{z_{P_y^2}} \\ C_{P_x^2} t_2^{x_{P_x^2}-1} S_2^{y_{P_x^2}} \upsilon_2^{z_{P_x^2}} \\ C_{P_z^2} t_2^{x_{P_z^2}-1} S_2^{y_{P_z^2}} \upsilon_2^{z_{P_z^2}} \end{pmatrix}; \tag{2}$$

$$\overline{p_{\Delta t}^1} = \begin{pmatrix} x_{P_x^1} t_1^{x_{P_x^1}-1} C_{P_x^1} S_1^{y_{P_x^1}} \upsilon_1^{z_{P_x^1}} \\ x_{P_y^1} t_1^{x_{P_y^1}-1} C_{P_y^1} S_1^{y_{P_y^1}} \upsilon_1^{z_{P_y^1}} \\ x_{P_z^1} t_1^{x_{P_z^1}-1} C_{P_z^1} S_1^{y_{P_z^1}} \upsilon_1^{z_{P_z^1}} \end{pmatrix}; \qquad \overline{p_{\Delta t}^2} = \begin{pmatrix} x_{P_y^2} C_{P_y^2} t_2^{x_{P_y^2}-1} S_2^{y_{P_y^2}} \upsilon_2^{z_{P_y^2}} \\ x_{P_x^2} C_{P_x^2} t_2^{x_{P_x^2}-1} S_2^{y_{P_x^2}} \upsilon_2^{z_{P_x^2}} \\ x_{P_z^2} C_{P_z^2} t_2^{x_{P_z^2}-1} S_2^{y_{P_z^2}} \upsilon_2^{z_{P_z^2}} \end{pmatrix}. \tag{3}$$

The value of the cutting force is calculated according to the well-known formula $p_1 = c_i t^{x_i} s^{y_i} v^{z_i}$ $i = x;\ y;\ z.$ depending on the parameter t [11].

The model of the scattering field of the performed dimensions on the transverse carriage in the opposite adjustment is similar. In non-opposite adjustment, there is no mutual influence of cutting forces. Therefore, scattering interval of distortion has a single positive position. The maximum of this interval occurs with large depths of cut on both carriages, maximum workpiece hardness and minimum flexibility of the technological system, and the minimum is obtained with reverse position. As a result, for the scattering field of the performed size on the longitudinal carriage in the non-opposite adjustment, we respectively obtain:

$$\Delta w_1 = \omega\left[e_{01} t_1 \overline{p_t^1} + e_0 t_2 \overline{p_t^2}\right] + \left[e_{01} \Delta t_1 \overline{p_{\Delta t}^1} + e_0 \Delta t_2 \overline{p_{\Delta t}^2}\right] + \omega\left[-(a_{O_1}^1 \xi_1 a_{O_1}^1 + a_{O_0}^0 \xi_0 a_{O_0}^0) t_1 \overline{p_t^1} - a_{O_0}^0 \xi_0 a_{O_0}^0 t_2 \overline{p_t^2}\right] +$$

$$+\left[-\left(a_{O_1}^1 \xi_1 a_{O_1}^1 + a_{O_0}^0 \xi_0 a_{O_0}^0\right) \Delta t_1 \overline{p_{\Delta t}^1} - a_{O_0}^0 \xi_0 a_{O_0}^0 \Delta t_2 \overline{p_{\Delta t}^2}\right]; \tag{4}$$

In the non-opposite adjustment, the model of the scattering field of the performed size on the transverse carriage is similar.

Most real multi-tool adjustments are not uniform in the direction of cutting forces. For this reason, there is no single calculation scheme for the scattering field for non-uniform directional adjustments. The calculated scheme of the scattering field is determined separately for each coordinate direction, so one adjustment can be opposite in the direction of one dimension to be performed, non-opposite to the direction of another dimension to be performed. If the adjustment in the considered direction is opposite, then some of the developed models (for example, model (1) for the longitudinal carriage) are applied in the direction of the considered dimension, and for non-opposite adjustments, some of the developed models are used in the direction of the considered dimension (for example, model (4) for the longitudinal carriage).

During double-tool machining on multipurpose CNC machines, as a result of the development of full-factor matrix mathematical models of errors in the dimensions performed using the appropriate input parameters for solving various problems of practical importance, some parameters should be determined experimentally. With the determination of the complex characteristics of the compliance of the technological system for each subsystem consisting of two matrix complexes – the elasticity of the subsystems along the coordinate axes and the coordinate matrix of compliance e, characterizing its mutual influence, and showing the resistance of the subsystems to its rotations around the coordinate axes and the angular matrix of elasticity ξ, which characterizes its mutual influence, we define a complex characteristic of the compliance of subsystems. Using this characteristic, it is possible to calculate the total distortion of the performed dimensions for a given adjustment [27].

During the assessment of the adequacy of the theoretical full-factorial model of dimensional distortion after installing the workpiece to level the error in the position and shape of the workpiece, we pre-machine it to a certain size of 75 mm. This, in turn, ensures an equal distribution of the depth of cut during subsequent machining. The initial machining is carried out with a small feed *s* and a depth of cut *t*. After that, by measuring its dimension with a micrometer, we note the result. To check the adequacy of the theoretical dependences, the theoretical and experimental values of the accuracy of the dimensions performed were compared. The analysis showed that these values are located quite close (for the cases indicated in the table and other cases, the difference does not exceed 10 %).

All experiments were carried out with an estimate of the average value taking into account the distribution of results and its correspondence to the theoretical model according to the Student's criterion. The required number of repetitions of experiments was determined by the Romanovsky criterion [28].

It should be noted that due to the fact that the depth of cut *t*, its change Δt, as well as the property of instability ω of the technological system are the cause of the appearance of a scattering field of the performed dimension, special attention was paid to these factors during the verification of the developed models. Other factors in the models under consideration, depending on the cutting conditions, are involved in the models through the cutting force.

The developed multi-factor matrix model, taking into account not only plane-parallel movements of technological subsystems, but also angular displacements around base points, forms the basis for a model of distortion of the performed dimensions in a double-carriage adjustment.

The study of mathematical models for the formation of errors in the dimensions performed makes it possible to perform accuracy calculations for various machining conditions. These models take into account the combined effect of a combination of factors – the characteristic of the rigidity of the subsystems of the technological system, the geometry of the cutting tools, the value of the bluntness of the tool, cutting conditions, etc.

To check the operability of the models, variants were calculated with different initial data that determine the action of the formula, that is, for various variants, a study of machining accuracy was carried out. The performance of accuracy models of multi-tool double-carriage machining was tested using the influence of technological factors and design dimensions of the adjustment on the value of the scattering field of the diametrical size performed by the longitudinal carriage during multi-tool double-carriage machining. As an example, Figure 1 shows the effect of the diametric dimension performed on the longitudinal carriage during multi-tool double-carriage machining on the value of the scattering field at its values $t_1 = 1…6$ mm, $t_2 = 1…4$ mm. Base variant: double-carriage machining – longitudinal and transversal carriage, cutting insert-*CNMG 120408 P04 4225 CoroKey*, workpiece – steel 45, tolerance grade – $ITP_1 12$, $ITP_2 12$, dimensions of the workpiece $D = L = 74.9$ mm, cutting speed $V_1 = V_2 = 200$ m/min, feed $s_1 = s_2 = 0.24$ mm/rev, $\omega \approx 0.2$, coordinates of connecting vectors of points O_0 and O_1 relative to the base points of application of forces $\overline{P^1}$ and $\overline{P^2}$: $X_0 = 74.9$ mm, $Y_0 = 37.45$ mm, $X_1 = 136$ mm, $Y_1 = 130$ mm. Changes indicated for another option.

3 pivot (links) points are highlighted on the graphs: ● – $t_1 = 2$ mm, $t_2 = 2$ mm ▲ – $t_1 = 3$ mm, $t_2 = 1$ mm and ■ – $t_1 = 1$ mm, $t_2 = 3$ mm. In the base variant (Fig. 1, *a*), for each control point, it is shown on which branch of the graph it is located. But in the variant (Fig. 1, *b*), the sliding of these points relative to the base variant is shown on the corresponding form of labels (tags). From figure 1 it can be seen that, the nature of the Δw curves completely coincides with the embedded opinion for the opposite and non-opposite adjustments, that is, they have 3 branches (sleeves).

In fig. 1, *b* shows the effect on the error of the formed diametrical dimension on the longitudinal carriage during an increase of 12 times in comparison with the base version of the ratio of the length of the workpiece to the diameter. From this it can be seen that the error of the diametric dimension formed at this time on the longitudinal carriage changes at the base points from a decrease of –1,989 % to an increase of +376 %. In general, the carried out studies have shown that with an increase in the ratio of the length of the workpiece to the diameter in comparison with the base variant by 2 times, 3 times, 5 times, 10 times, the error of the formed diametrical dimension on the longitudinal carriage changes accordingly at the base points

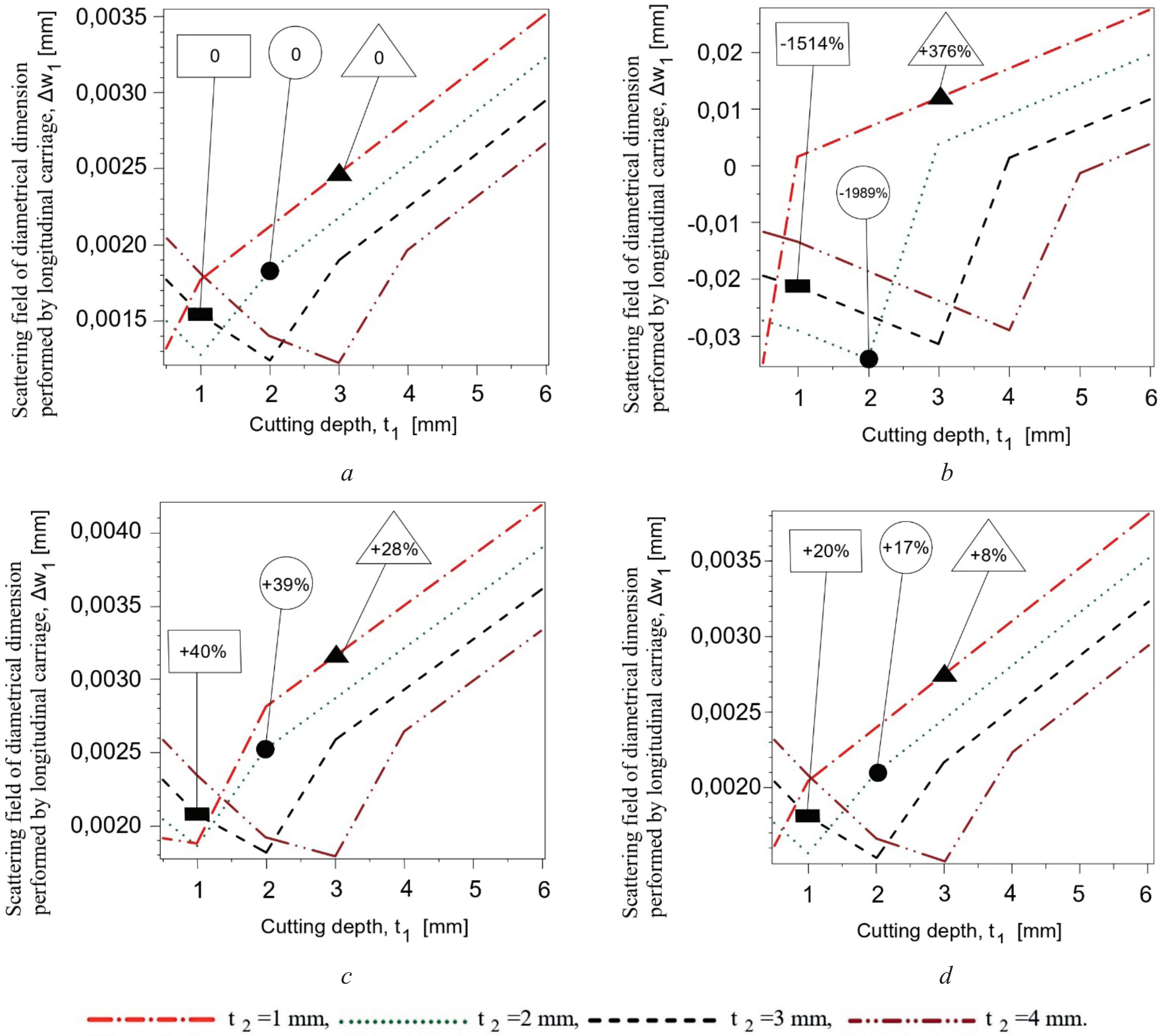

Fig. 1. Influence of cutting depths in longitudinal and cross carriages on the value of scattering field of diametrical dimension performed by longitudinal carriage in multi-tool two-carriage processing:
a – base variant; *b* – X_0 = 898.8 mm; *c* – $ITP_1 13$; *d* – $ITP_2 13$

from a decrease of -27 % to an increase of 4 %, from a decrease of -73 % to an increase of 16 %, from a decrease of –220 % to an increase of 56 %, from a decrease of –1,040 % to an increase of 256 %. Such a change in the error is explained by possible angular displacements associated with the turning moments of the technological system. During machining with a turning tool located on the transverse carriage, a decrease in the accuracy of the workpiece by one tolerance grade increases the error of the diametrical dimension (in comparison with the base points) with the turning tool located on the longitudinal carriage by 8–20 %.

At the same time, a decrease in the accuracy of the workpiece by one tolerance grade for the performed diametrical dimension with a turning tool located on the longitudinal carriage practically affects the diameter error by 28–40 %.

The size of the machine tool turret and the coordinates of the tool relative to the center of the turret are also important factors. With an increase in these coordinates relative to the base variant by 2 times and 1.5 times, a change in the error of the formed diametrical dimension, respectively, at the base points, from a decrease by 60 % to an increase by 44 % and from a decrease by 20 % to an increase by 17 % was observed.

In fig. 2 shown the influence of technological and design factors on plane-parallel displacements and angular displacements around the base points of the technological system at the value of the diametric dimension performed on the longitudinal carriage during multi-tool double-carriage machining equal to the scattering field. The base variant is the same as in fig. 1 and shows the changes for another option. Here, taking a two-fold value of the ratio of the length of the workpiece to its diameter (X_0 = 149.8 mm, Y_0 = 74.9 mm, X_0 / Y_0 = 2), as a base variant (Fig. 2, *a*), shown the percentage quantitative expression of plane-parallel displacements and angular displacements around the base points at the values of the diametrical dimension formed on the longitudinal carriage, equal to the scattering field during the increase in the length of the part by 6 times. And here 3 pivot points (links) are highlighted on the graphs: ● – t_1 = 2 mm, t_2 = 2 mm; ▲ – t_1 = 3 mm, t_2 = 2 mm and ■ – t_1 = 1 mm, t_2 = 2 mm. In the base variant (Fig. 2, *a*), for each pivot point it is shown on which of the graph branches it is located. In fig. 2, *a*, if we pay attention to the base variant, we will see that for this variant, the percentage quantitative expression of angular displacements around the base points at the pivot points is – for ● 10 % (respectively, linear displacements 90 %), for ▲ 15 % (respectively, linear displacements 85 %) and for ■ – 125 % (respectively, linear displacements 225 %).

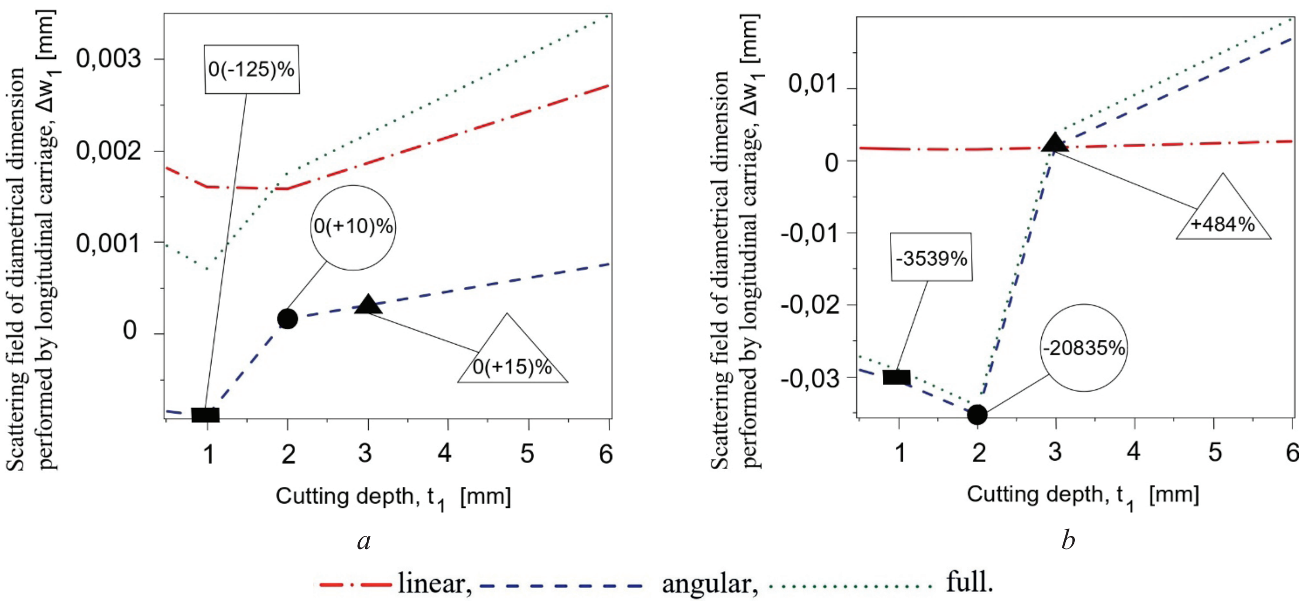

Fig. 2. Influence of technological and design factors of angular displacements around base points and plane-parallel displacements of the technological system at the value of the diametric size being performed on the longitudinal support with multi-tool two-carriage processing equal to the scattering field:
a – X_0 = 149.8 mm (base variant); *b* – X_0 = 898.8 mm

Since for the case ■ linear displacements and angular displacements occur in different directions, in its total value its quantitative expression as a percentage is obtained inverse to each other. In this case, the ratio of linear movements to angular movements is 0.56. However, this ratio changes in other variants.

Studies show that with an increase in the ratio of the length of the workpiece to its diameter by 1.5 times, 2.5 times, 5 times, the value of the scattering field of the diametrical dimension performed on the longitudinal carriage changes accordingly at the base points from a decrease of –312 % to an increase of 12.5 %, from a decrease of –684 % to an increase of 67 %, from a decrease of –14,424 % to an increase of 384 %. And here such a change in the error is explained by possible angular displacements associated with the turning moments of the technological system. The increase in negative percentages is explained by the increase in angular displacements in the total displacement.

Figure 1 shows the effect of the depth of cut on the machining error, however, during design, other parameters are more beneficial for control – feed on the longitudinal carriage and the transverse carriage. The influence of these factors is shown in Fig. 3.

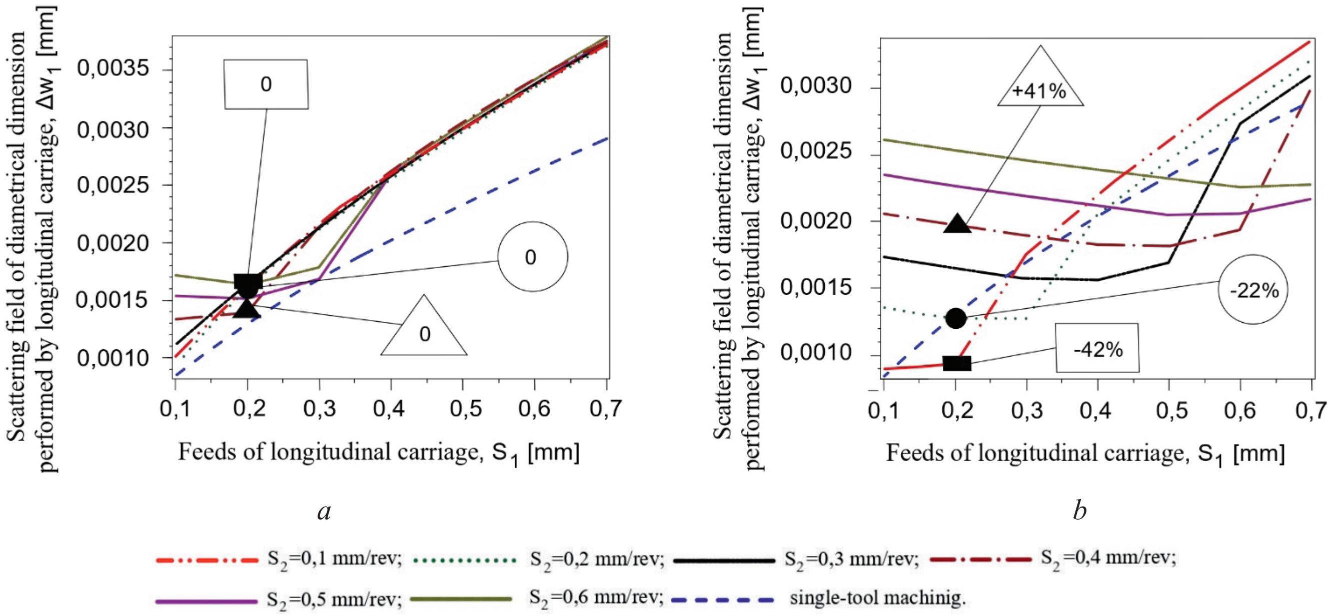

Fig. 3. Influence of feed and other technological factors on value of scattering field of diametrical dimension performed by longitudinal carriage in multi-tool double-carriage processing. Base variant: cutting depths $t_1 = t_2 = 2$ mm:

a – base variant; *b* – $t_2 = 4$ mm

Fig. 3 shows the influence of feed and other technological factors on the value of the scattering field of the diametrical dimension performed on the longitudinal carriage during multi-tool double-carriage machining. Here, the three pivot points are split like this: ● – $s_1 = 0.2$ mm/rev, $s_2 = 0.2$ mm/rev, ▲ – $s_1 = 0.2$ mm/rev, $s_2 = 0.4$ mm/rev and ■ – $s_1 = 0.2$ mm/rev, $s_2 = 0.1$ mm/rev. The base variant is the same as in Figure 1 and the change is shown for the other option. In the base variant (Figure 3 (a)), it is shown on which branches of the graph these points are located. And the signs of the corresponding form indicate what benefit is given by changing the machining conditions for each variant. Variant (b) of Figure 3 shows that multi-tool double-carriage machining at certain values can give lower error values compared to single-tool machining. It has been established that by changing feeds during multi-tool double-carriage machining in comparison with single-tool machining, it is possible to provide higher accuracy. When controlling feeds and changing other processing conditions, it is possible to significantly reduce or increase the machining error: for point ■ from 42 % to +250 %, for point ● from 2,014 % to + 38 %, for point ▲ from 2,356 % to +1,602 %.

Thus, once again we are convinced that the feeds of the carriages during double-carriage machining are an effective management tool. The established operability of the developed models and the total number of factors considered, as a result, make it possible to use it as the basis of a model for managing multi-tool double-carriage machining.

Results and its discussion

We offer full-factor models of scattering fields of the performed dimensions during multi-tool machining on multi-purpose CNC machines. These models take into account the elasticity of the technological system in all 6 degrees of freedom and thus make it possible to take into account both plane-parallel and angular displacements around the base points of the technological system.

To check the performance of the models, variants with different initial data that determine the influence of the formula are calculated, that is, theoretical studies of the machining accuracy are carried out for various options. During theoretical studies in the models of distortion and scattering of the performed dimensions in the double-carriage adjustment, the dependences on the technological parameters of both plane-parallel and angular displacements around the base points of technological subsystems are considered separately. The influence to a large extent on an increase in angular displacements with an increase in the length of the workpiece is clearly displayed using the developed models. And this shows the need to take into account the influence of angular displacements when processing non-rigid parts.

The developed theoretical full-factor models of dimensional distortion for double-carriage adjustments reflect the influence of the main technological and design factors and, for this reason, can be used in the design of operations to take into account the accuracy requirements.

The established operability of full-factor matrix models and scope of its action, as a result, make it possible to use it as the basis of models for managing multi-tool double-carriage machining. The study of mathematical models for the formation of errors in the performed dimensions makes it possible to calculate the accuracy for various machining conditions. These models take into account the combined effect of a combination of factors – the characteristic of the rigidity of the subsystems of the technological system, the geometry of the cutting tool, the value of the bluntness of the tool, cutting conditions, etc.

On the basis of the developed models, it is possible to determine the level of influence of a complex of technological factors on machining accuracy – the structure of multi-tool adjustments, the deformation properties of the subsystems of the technological system, cutting conditions. The developed models make it possible to predict the accuracy of machining for given conditions (structure of adjustment, properties of the technological system, machining conditions), creating a methodlo-gical basis for computer-aided design systems for multi-tool turning.

The developed full-factor matrix models of scattering fields of the performed dimensions in multi-tool double-carriage adjustments make it possible to calculate the error values of each performed dimension at the design stage for various adjustments and thereby create conditions for justifying the best option. To use this model in a real technological process, it is necessary to go either to a possibly set or possibly measurable value of a parameter of a real part or workpiece. For example, $\Delta w1$ – here, under the action of the cutting force, it calculates the constituent scattering field caused by the elastic deformations of the technological system. At the same time, only the total scattering field can be determined here. The model takes into account the change in the depth of cut, but we can really estimate the primary error of the workpiece.

The presence of the actual complex matrix compliance characteristic for a real machine tool makes it possible to evaluate the practical applicability of the developed matrix models of machining accuracy.

The developed models make it possible to determine the maximum permissible values of cutting conditions. In this way, for a given precision, the highest productivity during machining can be ensured.

The developed models of displacements during solving the problem of designing machining on multipurpose CNC machines can be transformed into control models. Due to the fact that the developed models take into account the coordinate and angular displacements, it is possible to work according to the requirements of the scattering field values of the performed dimensions and the shape error of the control models.

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Conflicts of Interest

The authors declare no conflict of interest.