Modeling the influence of geometric errors of vertical-milling machines on the accuracy of the complex of treated surfaces

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Abstract. The actual problem of modeling the influence of geometric errors of vertical milling machines on the accuracy of machined surfaces is considered in the paper. For the first time, a mathematical model of the accuracy of vertical milling machines is presented when processing a complex of keyway surfaces. The model was developed on the basis of a variational method for calculating the accuracy of metal-cutting systems, which is a development of the well-known variational method for calculating the accuracy of machine tools. The results of modeling the influence of geometrical errors of vertical milling machines on the accuracy of the machined surfaces of the keyway are given. Directions for further research of milling accuracy modeling with variable values of machine tool geometries are proposed. The work is useful for researchers engaged in research of the accuracy of technological equipment.

Keywords: vertical milling machine, geometrical errors, machining accuracy

1. Introduction

The main indicators characterizing the machining process are the geometrical accuracy of both the machine tools and the surfaces processed on these machines. At the beginning of the 20th century, Professor Schlesinger laid the foundations for studying the influence of the geometrical errors of machine tools on the accuracy of machined surfaces [1]. Despite the development of methods and approaches for determining the geometrical accuracy of machine tools [2], the main method remains the variational method for calculating the accuracy of machine tools developed by professors D.N. Reshetov and V.T. Portman [3, 4], which was developed in [5-10]. In this paper, attention is paid to the accuracy of milling, as it constitutes a significant share among the various types of treatments.

2. General mathematical model of milling accuracy

In [9], a new definition of the vector balance of the accuracy of a cutting machine was introduced, which included only those geometrical errors of the machine that had a direct impact on the accuracy of machining a given surface. In this paper, the structure of the modified model of the output accuracy of the machine is proposed, on the basis of which the well-known variational method for calculating the accuracy of machine tools has gained further development. In [10], the full development of the classical variational method for calculating the geometric accuracy of machines in a variational method for calculating the accuracy of metal-cutting systems is presented, including separation of errors in size, shape and position, mathematical justification for their calculation and compliance with current standards for the norms of machine accuracy, and accumulated experience in these areas [16].

The basis of the classical variational method for calculating the accuracy of machine tools is to determine their capabilities in processing various surfaces by means of the shaping function using specified cutting tools. Moreover, the shaping function has the form [3,4]:

$$r_0 = A_0 \cdot r_l,$$

(1)
where \( r_0 \) is the radius-vector connecting the coordinates of the points of the cutting tool in the coordinate systems of the cutting tool itself and the workpiece; \( A_{0,l} = \prod_{i=1}^{l} A_{i,i-1}^l \); \( l \) is the number of moving parts FS machine; the matrices \( A \) included in the product correspond to one of the six generalized displacements performed by the link (node); \( r_1 \) is the radius-vector of forming points (cutting edge) of the tool.

Accounting in expression (1) of the equations of relations between generalized displacements [3,4]:

\[
f_j(q_1, ..., q_{n+m}) = 0; j = 1, ..., L,
\]

where \( q_1, ..., q_{n+m} \) are the variables included in the matrix \( A_{0,l} \); \( n \) is the number of links that carry out the movement of shaping; \( m \) is the number of independent variables included in the model of the cutting tool; \( L \) is the number of links, \( L = n + m - 2 \),

allows to obtain the equation of nominal surface to be treated:

\[
r_0 = r_0(u, v, q_0), \tag{3}
\]

where \( u, v \) are curvilinear coordinates of the surface; \( q_0 \) is the vector of dimensional surface parameters; \( q_0 = (q_{01}, ..., q_{0m})^T \); \( m1 \) is the number of components of the vector \( q_0 \).

The model structure of the output accuracy of the machine [3,4] is based on the definition of vector and scalar accuracy balances, as well as the concept of a base surface. Vector balance of accuracy of the machine \( \Delta r_0 \) is a variation of its shaping function without taking into account the errors of the cutting tool:

\[
\Delta r_0 = \sum_{i=0}^{l} A_{0,i} \varepsilon_i A_i l r_l, \tag{4}
\]

where \( \varepsilon_i \) is the error matrix of the relative position of the coordinate systems:

\[
\varepsilon_i = \begin{pmatrix}
0 & -\gamma_i & \beta_i & \delta_{x_i} \\
\gamma_i & 0 & -\alpha_i & \delta_{y_i} \\
-\beta_i & \alpha_i & 0 & \delta_{z_i} \\
0 & 0 & 0 & 0
\end{pmatrix}, \tag{5}
\]

where \( \delta_{x_i}, \delta_{y_i}, \delta_{z_i} \) are the small displacements of the coordinate system \( S_i \) along the \( X, Y, Z \) axes; \( \alpha_i, \beta_i, \gamma_i \) are the small angles of rotation of the coordinate system \( S_i \) with respect to the \( X, Y, Z \) axes , taking into account the bond variation (2):

\[
\sum_{i=1}^{n+m} \frac{\partial f_j}{\partial q_i} \delta q_i = \delta f_j, \quad j = 1, 2, ..., L. \tag{6}
\]

For metrological evaluations, the scalar accuracy balance \( \Delta r_n \) is used, which is the projection of the vector \( \Delta r_0 \) onto the normal to the nominal surface \( r_0 \), i.e. \( \Delta r_n = n^T \Delta r_0 \), where \( n \) is the unit normal vector; \( t \) is the transpose symbol.

To determine the base surface \( r_b \) in [3,4] two representations are given:

\[
r_b = r_0(u, v, q), \tag{7}
\]

where \( q \) is the base surface parameter vector,

and

\[
r_b = r_0 + \varepsilon_b r_0 + d r_0 + \delta r_0. \tag{8}
\]

where \( \varepsilon_b \) is the error matrix of the location of the coordinate system associated with the base surface; \( d r_0 \) is the total differential of the radius-vector \( r_0 \), taken over all components of the vector \( q_0 \); \( d r_0 = \sum_{i=1}^{m} (\partial r_0/\partial q_i) \Delta q_i \); \( \delta r_0 \) is the vector of the shape error of the nominal surface, i.e. in a specified way distorting a nominal surface.

Expressions (1) - (8) are basic in the linearized formulation for the application of the variational method for calculating the accuracy of machine tools, described in the works [3,4,11].

With the development of this method in [6, 9, 10, 12, 13], two new definitions of the vector balance of accuracy \( \Delta r_0^* \) and \( \Delta r_0^{**} \) were introduced.

The vector balance of accuracy \( \Delta r_0^* \) is determined only by expression (4) without taking into account the equations of connections (2) and their variations (6), fully describes the vector of machine errors at each point of its working space.

The vector balance of accuracy \( \Delta r_0^{**} \) is determined by expressions (4) and (6), but includes only those geometrical errors of the machine, which are included in the scalar balance of accuracy \( \Delta r_n \). Introduction to the consideration of the balance \( \Delta r_0^{**} \) allowed to give a new definition of the real treated surface \( r \):
\[ r = r_0 + \Delta r_0^* , \]  
\[ r = r_0 + \varepsilon_0 r_0 + \delta r_0 + dr_0. \]

Expressions (9) and (10) do not include those geometrical errors of machine tools, which although the influence on the machining accuracy, but have a second order of smallness, since their projections onto the normal to the surface being treated are zero.

In expression (10), the matrix \( \varepsilon_0 \) completely determines the change in the position of the workpiece during the processing of the surface \( r_0 \) relative to the used technological base and does not lead to errors of size and shape [6].

The components \( dr_0 \) and \( \delta r_0 \) of expressions (10) determine the size and shape errors for the actual treated surface.

On the basis of the introduced definitions in [12], a new approach to the construction of a system for estimating the accuracy of machined surfaces was proposed. In [13], relations between the parameters of its geometrical accuracy and the deviations of an arrangement of surfaces processed on it for one installation were established [17-19].

Using the proposed method allows performing mathematical modeling of the accuracy of machining the surfaces of the keyway on vertical milling machines of models 6P10, 6A56, 6A59, 6D12 (Fig. 1) with the shaping function [14]:

\[ r_0 = A^1(x)A^2(y)A^3(z)A^6(\phi)r_u = \begin{pmatrix} R \cos(\varphi + \frac{2\pi j}{n}) + x \\ R \sin(\varphi + \frac{2\pi j}{n}) + y \\ z \\ 1 \end{pmatrix}, \]

where \( A^1(x), A^2(y), A^3(z) \) is the displacement matrices along the \( X, Y \) and \( Z \) axes, respectively; \( A^6(\varphi) \) is the rotation matrix around the \( Z \) axis; \( r_u \) is the equation for a cylindrical end milling cutter:

\[ r_u = (R\cos\frac{2\pi j}{n}; R\sin\frac{2\pi j}{n}; 0; 1)^T, \]

\( R \) is the cutter radius; \( j = (1, \ldots, n) \) is the cutter blade number; \( n \) is the number of cutter blades; \( \varphi \) is the angle defining the position of the blade on the surface of the cutter cylinder; \( z \) is the independent variable that has the meaning of linear displacement along the \( OZ \) axis \( (0 \leq z \leq c, c \) is the cutter length (groove depth)).

![Figure 1. Forming system of vertical milling machine and complex nominal machined surfaces keyway](image-url)
The peculiarity of the machining process under consideration is that when milling a closed keyway with one cutting tool with two cutting edges, the machine processes three types of surfaces in one pass: flat side, semi-cylindrical and flat surface of the bottom of the groove [20]. When processing this complex of surfaces with a milling cutter with a radius of \( R \), the equations of the connections are of the form: \( x = 0; \ z = c; \ y \in [0, L] \), \( L \) is the length of the keyway. The general equation (11) for all nominal surfaces to be treated is:

\[
r_0 = (R \cos(\varphi + \frac{2\pi j}{n}); \ R \sin(\varphi + \frac{2\pi j}{n}) + y; \ z; 1)^T.
\]

Let us consider the vector balances and their components for each type of machined surfaces on a milling machine.

1. **Lateral flat surfaces.** Vector balance \( \Delta r_{0p}^{**} \) and its components are equal to:

\[
\Delta r_{0p}^{**} = \begin{pmatrix}
-\varphi_0 y_0 + z \beta_0 + \delta x_0 \\
\mp R \gamma_0 - z \alpha_0 + \delta y_0 \\
+R \beta_0 + y \alpha_0 + \delta z_0
\end{pmatrix}.
\]

\[
\varepsilon_0 r_{0p} = \begin{pmatrix}
\frac{\varphi_0 y_0 + z \beta_0 + \delta x_0}{\mp R \gamma_0 - z \alpha_0 + \delta y_0} \\
\frac{\mp R \beta_0 + y \alpha_0 + \delta z_0}{0}
\end{pmatrix}.
\]

\[
\delta r_{0p} = \begin{pmatrix}
\frac{z \sum_{i=0}^{1} \beta_i - \gamma y_1 + \delta x_4 \cos \frac{2\pi j}{n} + \delta y_4 \sin \frac{2\pi j}{n}}{\mp R \sum_{i=1}^{4} y_i - z \sum_{i=1}^{4} \alpha_i + \delta x_4 \sin \frac{2\pi j}{n} + \delta y_4 \cos \frac{2\pi j}{n}} \\
\frac{\mp R \sum_{i=1}^{3} \beta_i + y \sum_{i=1}^{4} \alpha_i + \alpha_4 R \sin \frac{2\pi j}{n} - \beta_4 R \cos \frac{2\pi j}{n}}{0}
\end{pmatrix}.
\]

\[
dr_{0p} = (\sum_{i=1}^{1} \delta x_i; \sum_{i=1}^{3} \delta y_i; \sum_{i=1}^{4} \delta z_i; 0)^T.
\]

2. **Semi-cylindrical surfaces.** Vector balance \( \Delta r_{0c}^{**} \) and its components are equal to:

\[
\Delta r_{0c}^{**} = \begin{pmatrix}
-\varphi_0 y_0 \sin \left( \varphi + \frac{2\pi j}{n} \right) + z \sum_{i=0}^{1} \beta_i - L \sum_{i=0}^{1} y_i + \\
\mp R \sum_{i=0}^{4} \gamma_i \sin \left( \varphi + \frac{2\pi j}{n} \right) + R \sum_{i=0}^{4} \beta_i \cos \left( \varphi + \frac{2\pi j}{n} \right) - \\
\mp R \sum_{i=0}^{3} \alpha_i \beta_0 + \delta x_4 \cos \varphi + \delta y_4 \sin \varphi + \sum_{i=0}^{3} \delta x_i; \ R \sum_{i=0}^{4} y_i \cos \left( \varphi + \frac{2\pi j}{n} \right) - \\
\mp R \sum_{i=0}^{3} \alpha_i \gamma_0 \sin \left( \varphi + \frac{2\pi j}{n} \right) - R \sum_{i=0}^{4} \beta_i \cos \left( \varphi + \frac{2\pi j}{n} \right) + L \sum_{i=0}^{1} \alpha_i + \\
+\alpha_4 R \sin \frac{2\pi j}{n} - \beta_4 R \cos \frac{2\pi j}{n} + \sum_{i=0}^{4} \delta z_i; 0
\end{pmatrix}.
\]

\[
\varepsilon_0 r_{0c} = \begin{pmatrix}
\frac{-\varphi_0 y_0 \sin \left( \varphi + \frac{2\pi j}{n} \right) + z \beta_0 - L \gamma_0 + \delta x_0}{R \gamma_0 \cos \left( \varphi + \frac{2\pi j}{n} \right) - z \alpha_0 + \delta y_0; \ R \alpha_0 \sin \left( \varphi + \frac{2\pi j}{n} \right) - \\
\frac{-R \beta_0 \cos \left( \varphi + \frac{2\pi j}{n} \right) + L \alpha_0 + \delta z_0}{0}
\end{pmatrix}.
\]
\[ \delta r_{od} = -R \sum_{i=1}^{4} y_i \sin \left( \frac{2\pi i}{n} \right) + z \sum_{i=1}^{2} \beta_i - L \gamma_1 + \sum_{i=0}^{4} y_i + \delta x_4 \cos \phi - \delta y_4 \sin \phi; R \sum_{i=1}^{4} y_i \cos \left( \frac{2\pi i}{n} \right) - \sum_{i=0}^{4} y_i + \sum_{i=0}^{4} \beta_i \sin \phi; \]

\[ R \sum_{i=1}^{3} \alpha_i \sin \left( \frac{2\pi i}{n} \right) - R \sum_{i=0}^{3} \beta_i \cos \left( \frac{2\pi i}{n} \right) + L \alpha_1 + \alpha_4 \sin \left( \frac{2\pi i}{n} \right) - \beta_4 \cos \left( \frac{2\pi i}{n} \right) \]

In expressions (18) - (20) L=0 - for one semi-cylindrical surface, L=|L| for another one.

\[ dr_{oc} = dr_{op} \]

3. The surface of the bottom keyway. Vector balance \( \Delta r_{od}^\star \) and its components are equal to:

\[ \Delta r_{od}^\star = \begin{pmatrix} -R \sum_{i=0}^{4} y_i \sin \left( \frac{2\pi i}{n} \right) + c \sum_{i=0}^{2} \beta_i - y \sum_{i=0}^{1} y_i + \delta x_4 \cos \phi - \delta y_4 \sin \phi; R \sum_{i=0}^{4} y_i \cos \left( \frac{2\pi i}{n} \right) - \sum_{i=0}^{4} y_i + \sum_{i=0}^{4} \beta_i \sin \phi; \\
R \sum_{i=0}^{3} \alpha_i \sin \left( \frac{2\pi i}{n} \right) - R \sum_{i=0}^{3} \beta_i \cos \left( \frac{2\pi i}{n} \right) + y \sum_{i=0}^{1} \alpha_i + \alpha_4 \sin \left( \frac{2\pi i}{n} \right) - \beta_4 \cos \left( \frac{2\pi i}{n} \right) + \sum_{i=0}^{4} \delta z_i; 0 \end{pmatrix} \]

\[ \varepsilon_{0r_{od}} = \begin{pmatrix} -R y_0 \sin \left( \frac{2\pi i}{n} \right) - c \beta_0 - y \gamma_0 + \delta x_0; \\
R y_0 \cos \left( \frac{2\pi i}{n} \right) - c \alpha_0 + \delta y_0; R \alpha_0 \sin \left( \frac{2\pi i}{n} \right) - y \sum_{i=0}^{1} \alpha_i + \alpha_4 \sin \left( \frac{2\pi i}{n} \right) - \beta_4 \cos \left( \frac{2\pi i}{n} \right) \end{pmatrix} \]

\[ \delta r_{od} = \begin{pmatrix} -R \sum_{i=1}^{4} y_i \sin \left( \frac{2\pi i}{n} \right) + c \sum_{i=1}^{2} \beta_i - y \gamma_1 + \delta x_4 \cos \phi - \delta y_4 \sin \phi; R \sum_{i=1}^{4} y_i \cos \left( \frac{2\pi i}{n} \right) - \sum_{i=1}^{4} y_i + \sum_{i=1}^{4} \beta_i \sin \phi; \\
R \sum_{i=1}^{3} \alpha_i \sin \left( \frac{2\pi i}{n} \right) - R \sum_{i=1}^{3} \beta_i \cos \left( \frac{2\pi i}{n} \right) + y \alpha_1 + \alpha_4 \sin \left( \frac{2\pi i}{n} \right) - \beta_4 \cos \left( \frac{2\pi i}{n} \right) \end{pmatrix} \]

Thus, expressions (13) - (25) determine the mathematical model of the accuracy of a vertical milling machine with a well-known shaping function when processing a complex of surfaces of a closed keyway on it.

3. Modelling the accuracy of milling at constant values of the geometrical errors of the machine

To further investigate the influence of geometric errors of a vertical milling machine on the accuracy of machined surfaces, we perform a simulation of the formation of errors of each real surface, namely errors: position, shape and size. Modeling of the influence under consideration was made using the graphical tools of the Maple system. The results are presented in Fig. 2 - 5.
Figure 2. Formation of position errors of real surfaces

Figure 3. Formation of errors in the shape of real surfaces

Figure 4. Formation of errors in the size of real surfaces

Figure 5. Formation of all types of errors of real surfaces

In fig. 2 - 5 nominal surfaces are shown in blue, real - in green. Also, special attention should be paid to the position of the axes $OX$, $OY$ and $OZ$: due to the static nature of the presented images of the surfaces, the positions of the axes change to achieve the greatest visibility when modeling pairs of surfaces relative to each other.

As a result of modeling the influence of the geometrical errors of the machine on the position errors of the real surfaces of the keyway groove (Fig. 2), the formation of size errors (displacement of surfaces along the $OZ$ axis) was revealed.

The results of the simulation of the influence of the geometrical errors of the machine on the shape errors of the real surfaces of the keyway (Fig. 3) indicate the formation of the total shape errors and the location of the surfaces, as well as size errors. In figure 3 not only the slopes of the surfaces are visible, but also their deviation from the nominal sizes. In addition, there is a deviation of the surface of the bottom of the keyway from the flatness, as well as a deviation from the cylindricity of semi-cylindrical surfaces. In cross-section, they have the shape of a semi-oval.

The result of the simulation of the influence of the geometrical errors of the machine on the size errors of the real surfaces of the groove (Fig. 4) was that the deviations of the surface sizes are formed relative to all 3 axes of coordinates, which entails the position errors of all the surfaces under
consideration (positional deviation). Dimensional errors in surface treatment appear the same: not only the keyway depth error \( \sum_{i=1}^{4} \delta z_i \), but also offset errors \( \sum_{i=1}^{4} \delta x_i \) and \( \sum_{i=1}^{4} \delta y_i \) along the axes \( OX \) and \( OY \) respectively.

From Figures 2-4, it can be seen that the shape, location and dimensions of all surfaces can be considered individually. However, the expediency of such studies lies in their joint study, i.e. in the presentation of the general keyway model (Fig. 5).

The formation of total errors in the shape and arrangement of the keyway, as well as errors in its size, is justified by the fact that the errors in the position and shape of surfaces have as their part identical manifestations, since caused by the same geometrical errors of the machine - non-perpendicularity of the spindle rotation axis to the working surface of the table in planes parallel and perpendicular to the longitudinal movement of the table. The reasons for this error can be spindle wavering (\( a_4, b_4, \delta x_4, \delta y_4 \)), geometric errors of the machine nodes (\( a_{0,3}, b_{0,3}, \delta x_{0,3}, \delta y_{0,3} \)), as well as errors in setting the size (\( \delta z_0, \delta z_{1-4} \)). It should be noted that the errors \( \gamma_0, \ldots, \gamma_4 \) have no impact on processing accuracy. In the mathematical model, they are presented for the full manifestation of the properties of the metal-cutting system.

4 The direction of further research of modeling milling accuracy

The importance of the results of the above modeling is due to consistency with the results of previous studies in this field [3-5, 15]. Additional operations of transformation and analysis of the structure of the relations between expressions (14) – (15, 17), (18) – (19, 21) and (22) – (23, 25) are necessary when the condition \( q_{cr} = q_{cr}(u, v) \).

So, the presence of wavering of a spin axis of a spindle \( \delta x_4 = a \cdot \cos (\varphi + \frac{2\pi j}{n}), \delta y_4 = b \cdot \cos (\varphi + \frac{2\pi j}{n}) \), provided \( a \neq b \), caused by errors in the manufacture and assembly of spindle unit bearings, leads not only to the error of the position of the real surfaces relative to the nominal surface, but also to the shape and size errors (Fig. 6). Here, the position error with respect to the technological base will be equal to \( \sqrt{a^2 + b^2} \), and the ratio between the shape and size errors depends on the ratio between the values: \( c, L, R, a \) and \( b \).

Figure 6. The influence of variable components \( \varepsilon_4 \) on the formation of errors of size, shape and position of a complex of real surfaces

Thus, the direction of further research of modeling accuracy of milling with the values of geometric errors associated with the coordinate movements of machine nodes is revealed.
5 Conclusions
A mathematical model of machining accuracy on vertical milling machines with a well-known shaping function, corresponding to machine models: 6P10, 6A56, 6A59, 6D12, when processing a complex of surfaces of a closed keyway on them is presented for the first time in this paper. The mathematical model is obtained using the provisions of the developed variational method for calculating the geometric accuracy of metal-cutting systems. The results of modeling the formation of errors: the position, shape and size of the real surface allow to conclude about the possible nature and numerical values of the influence of the geometric errors of a vertical milling machine on the accuracy of the surfaces processed on it. Besides, areas for further research on the model of machining accuracy with variable values of the geometrical errors of the machine are revealed in this paper.

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