Development of a method for diagnostics of the technical condition of spindles of metalworking machines

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Abstract. A method for operational diagnostics of the technical condition of drives of metalworking equipment is proposed. A method has been developed to improve the accuracy of machining spindles of metalworking machines using high-performance precision equipment. The development of the method was carried out on the basis of modeling and analysis of the runout of the axis of rotation (taking into account the process of shaping the surface of the part).

1. Introduction
The main task in modern industry is to constantly improve the accuracy of surface processing of spindles of metalworking machines. The domestic industry at the moment needs particularly precise products, and this entails the need for the calculation, design and production of metal-cutting machines that ensure high processing accuracy. At the same time the modern capabilities of the cutting tool must be implemented - cutting must be carried out at speeds up to 30 ... 50 m/s when cutting ferrous metals, 60 ... 80 m/s when cutting non-ferrous metals and 100 ... 120 m/s when abrasive processing.

The design of this kind of machine tools is impossible without increasing the accuracy of the spindle assembly as an element of the machine, which largely determines its accuracy.

At the present stage of development of machine tool construction, spindles on magnetic bearings are already used. Spindle units with rolling bearings are the most rigid, reliable and easy to use. In modern machine tools, and especially precision CNC machines, high-speed and power grinding machines, the radial and axial runout of the spindle should not exceed 1-2 microns.

To achieve such high indicators, it is necessary to know the main factors affecting the accuracy of the spindle rotation, as well as the possibility of their elimination or weakening of their influence. The accuracy of rotation depends on the accuracy of the manufacturing of the working surfaces of the bearings of the supports, measured on circular meters and optimometers.

Therefore, the accuracy of spindle rotation is increased, as a rule, by increasing the accuracy of manufacturing the bearings of the bearings and the surfaces of the spindle mating with them. This direction of increasing the accuracy has a limitation in the form of the level of development of technological processes of processing, achieved at a given time.

The main defects in manufacturing and assembly of equipment units include: imbalance of the spindle and its drive parts; errors in the manufacture and assembly of rolling bearings, rolling guides, rolling screw-nut transmission; errors in the manufacture and assembly of gear and belt drives; errors in the manufacture and assembly of electric motor elements. These defects cause vibration disturbances, which are concentrated in the places of manifestation of these defects. Therefore, the search for other
methods aimed at improving the accuracy of spindle rotation is an important scientific and practical task.

2. Main part
It is necessary to develop a method for determining the linear and angular coordinates of the unit vector of the axis of rotation $\overrightarrow{P_x}, \overrightarrow{P_y}, \overrightarrow{P_z}$ and the beating of this unit. Assess the accuracy of the method, i.e. what will be the indicators $\Delta P_x, \Delta P_y, \Delta P_z$. As an assumption, let us assume that rotation is without linear runout elements, there is no translational runout in the transverse and longitudinal planes.

![Figure 1. Measurement principle.](image)

Write down the rotation matrix:

$$M(P, \alpha) = \begin{bmatrix}
p_x p_x (1 - \cos \alpha) + \cos \alpha & p_x p_y (1 - \cos \alpha) + p_y \sin \alpha & p_x p_z (1 - \cos \alpha) - p_z \sin \alpha \\
p_y p_x (1 - \cos \alpha) - p_x \sin \alpha & p_y p_y (1 - \cos \alpha) + \cos \alpha & p_y p_z (1 - \cos \alpha) + p_z \sin \alpha \\
p_z p_x (1 - \cos \alpha) + p_x \sin \alpha & p_z p_y (1 - \cos \alpha) - p_y \sin \alpha & p_z p_z (1 - \cos \alpha) + \cos \alpha
\end{bmatrix}$$

(1)

where $\overrightarrow{P}$ - rotation vector, $\alpha$ - angle rotation vectors $\overrightarrow{A_1}, \overrightarrow{A_2}, \overrightarrow{A_3}$ around ort vector $\overrightarrow{P}$, and also used abbreviations $S_\alpha = \sin(\alpha), C_\alpha = \cos(\alpha), C_{1\alpha} = 1 - \cos(\alpha)$.

We represent the rotation matrix $M$ in the form of a matrix with the coefficients:

$$M(P, \alpha) = \begin{bmatrix}m_{11} & m_{12} & m_{13} \\
m_{21} & m_{22} & m_{23} \\
m_{31} & m_{32} & m_{33}\end{bmatrix}$$

(2)

Then each of the coefficients $m_{ij}$ can be written in the form:

$$m_{11} = P_x^2 C_{1\alpha} + C_\alpha \\
m_{12} = P_x P_y C_{1\alpha} + P_y C_\alpha \\
m_{13} = P_x P_z C_{1\alpha} - P_z C_\alpha \\
m_{21} = P_y P_x C_{1\alpha} - P_x S_\alpha \\
m_{22} = P_y^2 C_{1\alpha} + C_\alpha \\
m_{23} = P_y P_z C_{1\alpha} + P_z S_\alpha \\
m_{31} = P_z P_x C_{1\alpha} + P_x S_\alpha \\
m_{32} = P_z P_y C_{1\alpha} - P_y S_\alpha \\
m_{33} = P_z^2 C_{1\alpha} + C_\alpha$$

(3)
where the initial coordinates of the ray vectors are given $A_{x_1} = 0.01; A_{y_1} = 0.01; A_{z_1} = \sqrt{1 - A_{x_1}^2 - A_{y_1}^2}$.

We rotate the vector $A_1$ to the position $A_1'$ through the product of the matrix $M$ by $A_1$, the vector $A_2$ to the position $A_2'$, the vector $A_3$ to the position $A_3'$, dependencies are shown according to (4):

$$
\begin{align*}
A_1 &= M(P, \alpha) \cdot A_1 \\
A_2 &= M(P, \alpha) \cdot A_2 \\
A_3 &= M(P, \alpha) \cdot A_3
\end{align*}
$$

We get dependence (5):

$$
\begin{pmatrix}
A_{1x}' \\
A_{1y}' \\
A_{1z}'
\end{pmatrix} = M(P, \alpha)
\begin{pmatrix}
A_{1x} \\
A_{1y} \\
A_{1z}
\end{pmatrix}
$$

Dependencies for coordinates $A_{2x}', A_{3x}$ will be written in a similar way. Of the 9 obtained matrix equations, we use only the first rows in the $x$ coordinate and form a system of linear equations:

$$
\begin{align*}
A_{1x}' &= m_{11}A_{1x} + m_{12}A_{1y} + m_{13}A_{1z} \\
A_{1y}' &= m_{21}A_{2x} + m_{22}A_{2y} + m_{23}A_{2z} \\
A_{1z}' &= m_{31}A_{3x} + m_{32}A_{3y} + m_{33}A_{3z}
\end{align*}
$$

We represent the system of linear equations in the form:

$$
A_{1x}' = A_{1x} \begin{pmatrix}
m_{11} \\
m_{21} \\
m_{31}
\end{pmatrix}
$$

On the left, we know all the components of the column vector $A_{1x}' = (A_{1x}', A_{2x}', A_{3x}')$, $A_{1x} = A_{1x}(m)$. Hence, it seems possible to write down the construction matrix:

$$
A_{1x} = \begin{bmatrix}
A_{1x} \\
A_{2x} \\
A_{3x}
\end{bmatrix}
$$

And also its inverse matrix:

$$
A_{1x}^{-1} = \begin{bmatrix}
A_{1x}^{-1} & A_{1y}^{-1} & A_{1z}^{-1} \\
A_{2x}^{-1} & A_{2y}^{-1} & A_{2z}^{-1} \\
A_{3x}^{-1} & A_{3y}^{-1} & A_{3z}^{-1}
\end{bmatrix}
$$

Values $A_{1x}, A_{1y}, A_{2x}, A_{2y}, A_{3x}, A_{3y}, A_{1x}', A_{2x}'$, are found from a measurement experiment. The $x$ and $y$ coordinates on the matrix screen, and the $z$ coordinate by the formula:
\[
\begin{align*}
A_{z\z} &= \sqrt{1 - A_{x\z}^2 - A_{y\z}^2} \\
A_{x\z} &= \sqrt{1 - A_{z\x}^2 - A_{y\z}^2} \\
A_{y\z} &= \sqrt{1 - A_{x\z}^2 - A_{y\z}^2}
\end{align*}
\] (10)

\(A_{1z}, A_{2z}\) - similarly. Then we can get:

\[
A_{\text{inv}} A_{h} = A_{\text{inv}} A_{i\text{sub}} (m)
\] (11)

where \((m) = A_{\text{inv}} A_{h}\). Then:

\[
\begin{pmatrix}
m_{11} \\
m_{22} \\
m_{33}
\end{pmatrix} =
\begin{pmatrix}
A_{h,1}^{ab} A_{x} & A_{h,1}^{ab} A_{z} & A_{h,1}^{ab} A_{s} \\
A_{h,2}^{ab} A_{x} & A_{h,2}^{ab} A_{y} & A_{h,2}^{ab} A_{s} \\
A_{h,3}^{ab} A_{x} & A_{h,3}^{ab} A_{y} & A_{h,3}^{ab} A_{s}
\end{pmatrix}
\] (12)

Matrix equations are solved by the Gauss or Cramer method. Each of the values \(m_{11}, m_{22}, m_{33}\) – can take several values. Then consider the discrepancy of solutions:

\[
\begin{align*}
m_{11} - A_{1\text{sub}}^i &= 0 \\
m_{12} - A_{1\text{sub}}^i &= 0 \\
m_{13} - A_{1\text{sub}}^i &= 0
\end{align*}
\] (13)

We make sure that \(m_{11}, m_{22}, m_{33}\) are found correctly and are known. From matrix (1):

\[
\begin{align*}
m_{11} &= p_x^2 (1 - \cos \alpha) + \cos \alpha \\
m_{12} &= p_x p_y (1 - \cos \alpha) + p_z \sin \alpha \\
m_{13} &= p_x p_z (1 - \cos \alpha) - p_y \sin \alpha
\end{align*}
\] (14)

From where:

\[
P_x = \pm \sqrt{A_{h,1}^{ab} - C_{1a}}
\] (15)

\[
P_z = \sqrt{1 - P_x^2 - P_y^2}
\] (16)

\[
\begin{align*}
p_{y1} &= \frac{p_{a1}^2 S_a + p_{b1}^3 p_{a1}^1 C_{1a}}{S_a + p_{a1}^3 C_{1a}} \\
p_{y1} &= \frac{p_{a1}^2 p_{a1} C_{a1} - p_{b1}^3}{S_a}
\end{align*}
\] (17)

Verification:

\[
A_{\text{mod}} = p_{x1}^2 + p_{y1}^2 + p_{z1}^2
\] (18)
\( (m_{12}) = AM_{\rho_{12}}^2 = P_{\rho_{1}}^2 P_{\rho_{2}} C_{\rho_{1}} + P_{\rho_{2}} S_{\rho_{1}} \)
\( (m_{13}) = AM_{\rho_{13}}^2 = P_{\rho_{1}}^2 P_{\rho_{2}} C_{\rho_{1}} - P_{\rho_{2}} S_{\rho_{1}} \)

(19)

3. Conclusions
Thus, we have developed a technique (technology), which is fundamentally different from the pre-existing fact that with the aim of improving the accuracy of measurement of the position OB applied mathematical tools and algorithms for the calculation, provided that implement the mount end of the emitting device to one of the ends of the rotating parts.

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