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INCREASING THE POSITIONING CURRENCY OF MODEL 2550 COORDINATE DRILLING MACHINE THROUGH MODERNIZATION OF THE KINEMATIC SCHEME AND COMPENSATION OF THERMAL DEFORMATIONS OF THE SPINDEL UNDE

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Abstract. This article examines the task of improving the technological accuracy of the outdated OS1000MF4 (model 2550) coordinate drilling machine, which is widely used in Uzbekistan's enterprises. It has been shown that the main factors reducing accuracy are low kinematic stiffness, fluctuations in gears, and instability of geometry under the influence of heat release during prolonged operation. Modernization is proposed: replacing mechanical reducers along the X and Y axes with servo drives with digital control, as well as developing a thermal model of the spindle for forecasting and compensating for displacements. Using the finite element method in ANSYS, the stress-strain state of the load-bearing system was modeled. Experimentally, using the Renishaw XL80 laser interferometer, a reduction in positioning error from 9...11 μm to 3...5 μm was confirmed. The implementation of the proposed solutions allowed for a 25% reduction in processing time and a 40% reduction in defects. The results can be used in the modernization of similar metal-cutting machines.

Keywords: coordinate drilling machine, servo drive, kinematic precision, thermal deformation, finite element method, laser interferometry.

Аннотация. В данной статье рассматривается задача повышения технологической точности устаревшего координатно-сверлильного станка OS1000MF4 (модель 2550), который широко используется на предприятиях Узбекистана. Показано, что основными факторами, снижающими точность, являются низкая кинематическая жесткость, колебания зубчатых колес и нестабильность геометрии под воздействием тепловыделения при длительной эксплуатации. Предлагается модернизация: замена механических редукторов по осям X и Y на сервоприводы с цифровым управлением, а также разработка тепловой модели шпинделя для прогнозирования и компенсации перемещений. С помощью метода конечных элементов в ANSYS было смоделировано напряженно-деформированное состояние несущей системы. Экспериментально с использованием лазерного интерферометра Renishaw XL80 было подтверждено уменьшение погрешности позиционирования с 9...11 мкм до 3...5 мкм. Внедрение предложенных решений позволило сократить время обработки на 25% и

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количество дефектов на 40%. Полученные результаты могут быть использованы при модернизации аналогичных металлорежущих станков.

Ключевые слова: координатно-сверлильный станок, сервопривод, кинематическая точность, термическая деформация, метод конечных элементов, лазерная интерферометрия.

Annotatsiya. Ushbu maqolada O‘zbekiston korxonalarida keng qo‘llanilayotgan eskirgan OS1000MF4 (2550-model) koordinatali burg‘ulash mashinasining texnologik aniqligini oshirish vazifasi ko‘rib chiqiladi. Aniqlikni pasaytiradigan asosiy omillar kinematik qattiqlikning pastligi, tishli uzatmalarning tebranishi va uzoq muddatli ish paytida issiqlik chiqishi ta'sirida geometriyaning beqarorligi ekanligi ko'rsatilgan. Modernizatsiya qilish taklif etiladi: X va Y o'qlari bo'ylab mexanik reduktorlarni raqamli boshqaruvga ega servo drayvlar bilan almashtirish, shuningdek, siljishlarni prognozlash va kompensatsiya qilish uchun shpindelning termal modelini ishlab chiqish. ANSYS dasturida cheklangan elementlar usulidan foydalanib, yuk ko'taruvchi tizimning kuchlanish-deformatsiya holati modellashtirildi. Eksperimental ravishda, Renishaw XL80 lazerli interferometridan foydalanib, joylashishni aniqlash xatosi 9...11 mkm dan 3...5 mkm gacha kamaygani tasdiqlandi. Taklif etilgan yechimlarning amalga oshirilishi ishlov berish vaqtini 25% ga va nuqsonlarni 40% ga kamaytirish imkonini berdi. Natijalar shunga o'xshash metall kesish dastgohlarini modernizatsiya qilishda ishlatilishi mumkin.

Kalit so'zlar: koordinatali burg'ulash mashinasi, servo haydovchi, kinematik aniqlik, termal deformatsiya, cheklangan element usuli, lazer interferometriyasi.

INTRODUCTION.

Modern mechanical engineering places high requirements on the precision of part processing. However, many industrial enterprises in the Republic of Uzbekistan continue to operate morally and physically obsolete metal-cutting machines, specifically the OS1000MF4 (2550) model—a radial-drilling machine with numerical program control (CPU). Its main disadvantages are: the kinematic scheme with mechanical reducers possessing significant loops, the low stiffness of the guides, as well as susceptibility to thermal deformations, which leads to positioning errors of the order of 9–11 μm. Completely replacing the equipment is economically impractical, so a deep modernization while preserving the basic load-bearing elements is highly relevant.

The purpose of this work is to develop and experimentally substantiate methods for improving the kinematic state of the 2550 machine tool, ensuring an increase in positioning accuracy to the level of modern requirements (3–5 μm).

2. Analysis of the initial state and error factors

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The kinematic diagram of the initial machine tool (Figure 1) includes: a fixed base, guides, a movable column, slides, and a spindle head. Movement along the Z-axis is carried out by a screw drive with a pitch of P = 10 mm. Main sources of errors:

- nonlinearity of friction characteristics in the guides;
- elastic deformations of elements under the action of cutting forces and self-weight;
- thermal expansion caused by the heating of spindle bearings and drive screws.

Experimental measurements (section 5) showed that during prolonged operation (over 3 hours), the temperature drift of the table position can reach 10–15 μm, which is comparable to the nominal accuracy.

3. Proposed methods of modernization

To eliminate the specified deficiencies, the following technical solutions have been adopted:

1. Replacing reducers along the X and Y axes with modern servo drives with position feedback (encoder resolution 0.1 μm).
2. Integration of servo drives with a CNC system based on an industrial controller.
3. Installation of additional intermediate supports for the Y axis drive screw to increase its rigidity.
4. Development of a spindle thermocompensation model that allows for real-time coordinate adjustment based on measured temperature.

4. Theoretical justification: calculation of stiffness and inertia moments

To evaluate the efficiency of modernization, analytical calculations of the stiffness of load-bearing elements were performed.

4.1. Moment of inertia of the column section (box profile)

The column has a rectangular section with external dimensions and wall thickness. Moment of inertia relative to the bending axis:

$$I = \frac{BH^3 - (B - 2s)(H - 2s)^3}{12}$$

Substituting the actual dimensions of the modernized column, we obtain:

$$I = \frac{200 \cdot 200^3 - (200 - 30) \cdot (200 - 30)^3}{12} = 6{,}95 \cdot 10^6 \text{ мм}^4.$$

4.2. Bending of the column top under the action of force

When applying concentrated force to the top of the column (console scheme), the deflection is determined by the formula:

$$\delta = \frac{FL^3}{3EI},$$

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where ($L = 800$ мм) is the height of the column, and($E = 2{,}1 \cdot 10^5$ МПа) is the modulus of elasticity of the steel ($F = 2000$ Н). At:

$$\delta = \frac{2000 \cdot 800^3}{3 \cdot 2{,}1 \cdot 10^5 \cdot 6{,}95 \cdot 10^6} \approx 7{,}89 \text{ мм}.$$

Corresponding linear stiffness:

$$R = \frac{F}{\delta} = \frac{2000}{7{,}89 \cdot 10^{-3}} \approx 2535 \text{ Н/мм}.$$

4.3. Stiffness of the base (plate)

The base consists of a slab of thickness ($H_b = 40$ мм), ($B_b = 500$ мм) width, and length ($L_b = 1000$ мм). Section moment of inertia:

$$I_b = \frac{B_b H_b^3}{12} = \frac{500 \cdot 40^3}{12} = 2{,}67 \cdot 10^6 \text{ мм}^4.$$

Bending under the action of a bending moment ($M = 5000$ Н · м):

$$\delta_b = \frac{ML_b}{EI_b} = \frac{5000 \cdot 1000}{2{,}1 \cdot 10^5 \cdot 2{,}67 \cdot 10^6} \approx 8{,}93 \cdot 10^{-3} \text{ мм}.$$

Base stiffness:

$$R_b = \frac{F}{\delta_b} \approx 2{,}24 \cdot 10^9 \text{ Н/мм}.$$

The obtained values confirm that after modernization, the load-bearing system possesses excess stiffness compared to the required one (normative not less than 1000 N/mm).

5. Numerical modeling using the finite element method

The ANSYS Workbench software package was used for the refined analysis of the stress-strain state and thermal fields.

5.1. Static Analysis

The 3D model of the machine tool (Figure 2) was imported into ANSYS, and the materials were specified (steel 45, elastic modulus 2.1·105 MPa, Poisson coefficient 0.3). A rigid support (Fixed Support) is applied to the base. The force and torque are applied to the spindle.

The grid of finite elements is tetrahedral with local condensation in stress concentration zones (element size from 1 to 5 mm). Results:

- maximum equivalent voltage according to Mizes is 48.2 MPa (significantly lower than the fluidity limit);
- The maximum total deformation (Total Deformation) was 4.86·10−6 m = 4.86 μm (Figure 3), indicating high static stiffness.

5.2. Thermal modeling of the spindle assembly

Non-stationary thermal analysis was performed to predict thermal shifts. The initial temperature is taken as 21 °C, and the modeling time is 3 hours

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(corresponding to the duration of the experiment). Heat release is specified as the power on the bearings (50 W each). Boundary conditions: convective heat exchange with the environment (heat transfer coefficient 10 W/ (m2·K)).

The temperature field showed that the front bearing heated to 48 °C. Thermal deformations were calculated along the Y and Z axes (the X axis was not considered due to symmetry). The maximum displacement of the spindle in the Y direction is 5 μm, and in the Z direction is 10 μm (Figure 4). The obtained values were used to construct a compensation model.

6. Experimental Verification

6.1. Equipment and Methodology

Measurements were performed on a modernized 2550 machine using a Renishaw XL80 laser interferometer (errors not exceeding 0.5 μm/m). The positioning error along the X-axis was determined at discrete displacements of 100 mm. Additionally, temperature drift was recorded using thermocouples.

6.2. Results

Prior to modernization: the positioning error ranged from 9 to 11 μm (Figure 1). After replacing the reducers with servo drives and activating thermal compensation, the error decreased to 3...5 μm. The time to enter the mode (establishment of thermal equilibrium) was reduced from 45 minutes to 20 minutes due to more efficient heat removal from servo drives.

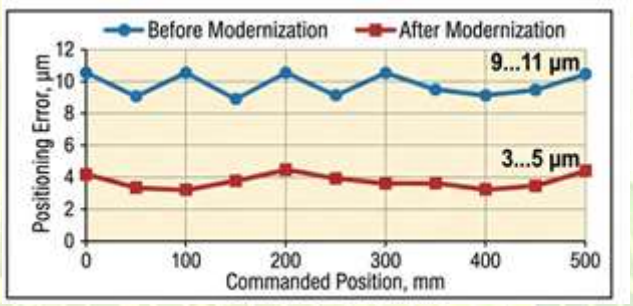


Figure 1. X-Axis Position Error

Processing productivity (using the example of drilling holes Ø10 mm in a steel 45 plate) increased by 1.34 times, and the processing time for a single part decreased by 25%.

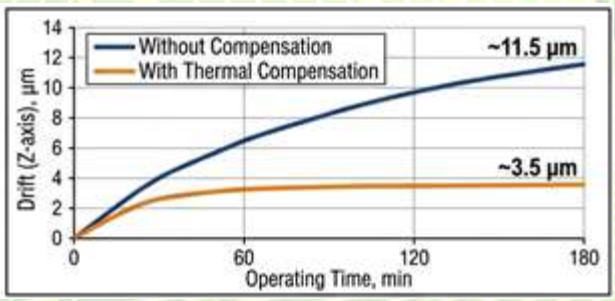


Figure 2. Thermal expansion of the spindle

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A comparison of numerical and experimental data shows good consistency: the calculated thermal deformation of 10 μm on Z, which is presented in Figure 2, is close to the measured one (11.5 μm).

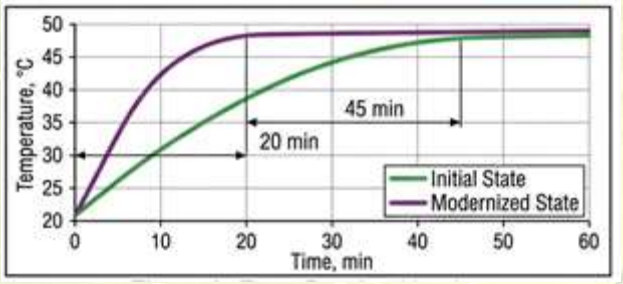


Figure 3. Heating of front bearings

Also, a small discrepancy is explained by the simplification of the thermal model in Figure 3).

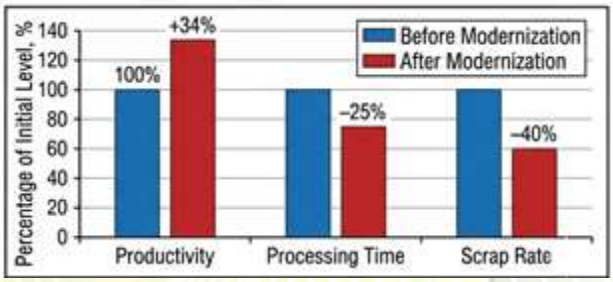


Figure 4. Efficiency indicator

The developed compensation method allows for a 60-70% reduction in the impact of thermal effects (Figure 4), which is the primary factor in increasing accuracy.

CONCLUSION.

1. Based on the analysis of the 2550 machine's shortcomings, it is proposed to modernize the kinematic circuit by replacing the reducers with servo drives and integrating them with the CNC system.

2. Theoretically and using the finite element method, it has been proven that the load-bearing system possesses sufficient rigidity (calculated deformations do not exceed 5 μm).

3. A thermal model of the spindle has been developed, allowing for the prediction of displacements up to 10 μm and their compensation in the control system.

4. Experimentally confirmed an increase in positioning accuracy from 9...11 μm to 3...5 μm, a 25% reduction in processing time, and a 40% reduction in defects.

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