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DEVELOPMENT OF SCIENTIFIC FOUNDATIONS FOR PREDICTIVE CONTROL OF THE FORMING ACCURACY OF MULTI-AXIS CNC MACHINE TOOLS UNDER TECHNOLOGICAL LOADS

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Abstract. This article investigates the scientific foundations for the predictive control of forming accuracy of multi-axis CNC machine tools under technological loads. The study comprehensively examines intelligent diagnostics based on drive current signals, a digital twin that takes into account the state of the rotary axis, real-time evaluation of deviations from the interpolated trajectory, prediction of dynamic changes in the milling process, detection of volumetric errors, and compensation methods based on iterative G-code modification. As a result, the accuracy of abnormal operating mode detection reached 95–97%, the time required for deviation detection was reduced from 15–20 minutes to 1–2 minutes, the positioning error decreased from 210–220 μm to 20–25 μm, motion accuracy along complex trajectories improved by 15–20%, and cutting tool life increased by 35%. The obtained results show that the integrated application of predictive control, intelligent adaptation, and compensation as an interrelated system represents an effective scientific and practical approach to ensuring high forming accuracy in multi-axis CNC machine tools.

Keywords: multi-axis CNC machine tool, predictive control, forming accuracy, technological load, intelligent diagnostics, digital twin, trajectory deviation, volumetric error, G-code compensation, regenerative chatter.

Annotatsiya. Ushbu maqolada texnologik yuklamalar sharoitida ko‘p o‘qli CNC dastgohlarida shakllantirish aniqligini bashoratli boshqarishning ilmiy asoslari tadqiq etilgan. Tadqiqotda yuritma tok signallariga asoslangan intellektual diagnostika, aylanuvchi o‘q holatini hisobga oluvchi raqamli egizak, interpolatsiyalangan trayektoriyadan og‘ishlarni real vaqt rejimida baholash,

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frezalash jarayonidagi dinamik o‘zgarishlarni prognozlash, hajmiy xatoliklarni aniqlash hamda G-kodni iteratsion o‘zgartirish asosida kompensatsiya qilish usullari kompleks tarzda ko‘rib chiqilgan. Natijada g‘ayritabiiy ish rejimlarini aniqlash aniqligi 95–97% ga yetkazildi, og‘ishlarni aniqlash vaqti 15–20 daqiqadan 1–2 daqiqagacha qisqartirildi, joylashish xatoligi 210–220 mkm dan 20–25 mkm gacha kamaytirildi, murakkab trayektoriyalar bo‘yicha harakat aniqligi 15–20% ga yaxshilandi hamda kesuvchi asbobning xizmat muddati 35% ga oshdi. Olingan natijalar bashoratli boshqaruv, intellektual moslashuv va kompensatsiyaning o‘zaro bog‘liq tizim sifatida qo‘llanilishi ko‘p o‘qli CNC dastgohlarda yuqori shakllantirish aniqligini ta’minlashning samarali ilmiy-amaliy yondashuvi ekanligini ko‘rsatadi.

Kalit so‘zlar: ko‘p o‘qli CNC dastgoh, bashoratli boshqaruv, shakllantirish aniqligi, texnologik yuklama, intellektual diagnostika, raqamli egizak, trayektoriya og‘ishi, hajmiy xatolik, G-kod kompensatsiyasi, regenerativ tebranish.

Аннотация. В данной статье исследованы научные основы прогнозного управления точностью формообразования многоосевых станков с ЧПУ в условиях технологических нагрузок. В работе комплексно рассмотрены методы интеллектуальной диагностики на основе сигналов тока приводов, цифрового двойника с учётом состояния вращательной оси, оценки отклонений от интерполированной траектории в реальном времени, прогнозирования динамических изменений процесса фрезерования, выявления объёмных погрешностей, а также компенсации на основе итерационного изменения G-кода. В результате точность выявления аномальных режимов работы достигла 95–97%, время обнаружения отклонений сокращено с 15–20 минут до 1–2 минут, погрешность позиционирования уменьшена с 210–220 мкм до 20–25 мкм, точность движения по сложным траекториям улучшена на 15–20%, а стойкость режущего инструмента увеличена на 35%. Полученные результаты показывают, что интегрированное применение прогнозного управления, интеллектуальной адаптации и компенсации как взаимосвязанной системы является эффективным научно-практическим подходом к обеспечению высокой точности формообразования многоосевых станков с ЧПУ.

Ключевые слова: многоосевой станок с ЧПУ, прогнозное управление, точность формообразования, технологическая нагрузка, интеллектуальная диагностика, цифровой двойник, отклонение траектории, объёмная погрешность, компенсация G-кода, регенеративные колебания.

INTRODUCTION.

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In modern mechanical engineering, multi-axis CNC (computer numerical control) machine tools are among the main technological means for manufacturing parts with complex spatial surfaces that require high accuracy and high quality. Many parts used in aviation, power engineering, instrument making, automotive manufacturing, and specialized mechanical engineering are produced precisely on five-axis and higher-coordinate machining systems. The advantages of such machine tools are determined by the flexibility of the machining trajectory, the possibility of generating complex shapes in a single setup, the reduction of production stages, and the improvement of overall technological productivity. At the same time, the complexity of the multi-axis machining process significantly complicates the problem of controlling forming accuracy.

In multi-axis CNC machine tools, forming accuracy is determined not only by the static accuracy specified in the machine passport, but also by the combined effect of dynamic, thermal, kinematic, and volumetric errors arising under real technological loads. During machining, variations in cutting forces, elastic deformations in the drives, backlash in rotary units, the condition of bearings, thermal expansion of the table and housing elements, deviations from the interpolated trajectory, and regenerative chatter negatively affect the actual geometry of the part. As a result, deviations from the specified contour, positioning errors, deterioration of surface quality, accelerated tool wear, and reduced stability of the machining process are observed [1].

In conventional control systems, the condition of the machine tool is usually controlled on the basis of preset machining parameters and standard compensation algorithms. However, such an approach does not sufficiently take into account time-varying technological loads, the actual condition of the machine units, the development of dynamic deviations, and the initial stages of potential failures. Therefore, in ensuring high accuracy along complex trajectories, conventional control methods often have limited effectiveness. In particular, in five-axis machine tools, kinematic inaccuracies associated with rotary axes, volumetric errors, and real-time load variations have a strong influence on forming accuracy.

In solving this problem, the predictive control approach has particular scientific and practical significance. Predictive control is understood as the continuous monitoring of the current technical condition of the machine tool, load variation, and the dynamic characteristics of the technological process, the preliminary assessment of their development trends, and the intelligent adjustment of control parameters accordingly. Such an approach makes it possible to integrate into a unified control loop such methods as diagnostics based on drive current signals, the use of digital twins, near-real-time detection of trajectory deviations,

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evaluation of volumetric errors, iterative G-code modification, and early prediction of regenerative chatter.

The relevance of this research topic lies in the fact that the forming accuracy of multi-axis CNC machine tools is considered not through a single factor, but as a comprehensive system within the chain of "diagnostics – prediction – compensation – intelligent adaptation." This makes it possible not only to observe the forming process, but also to evaluate it in advance and actively control it. In particular, the timely detection and compensation of errors arising under technological loads are important for increasing production efficiency, reducing rejects, lowering energy consumption, and extending tool life in high-precision machining processes [2].

At the same time, the issue of predictive control of forming accuracy in multi-axis CNC machine tools remains one of the insufficiently systematized scientific directions. Although in practice separate solutions are being applied, such as only diagnostics, only compensation, or only digital modeling, there remains a need to combine them within a unified scientific framework. It is precisely this circumstance that determines the scientific novelty and practical significance of the present study.

The purpose of this article is to develop the scientific foundations for the predictive control of forming accuracy of multi-axis CNC machine tools under technological loads, to systematize the main factors affecting accuracy, to evaluate the possibilities of applying predictive models based on intelligent diagnostics and digital twins, to determine the effectiveness of methods for compensating trajectory and volumetric errors, and to generalize the technological and economic results of the implemented solutions [3].

MATERIALS AND METHODS.

In the study, theoretical analysis, comparative analysis, predictive modeling, generalization of production results, and evaluation of implementation efficiency were used to assess the technological, dynamic, and geometric factors affecting the forming accuracy of multi-axis CNC machine tools.

The following implemented solutions were adopted as the practical basis of the research:

1. intelligent diagnostics of machine condition based on drive current signals;
2. development of a digital twin of the rotary axis of a five-axis CNC machine tool;
3. real-time calculation and predictive control of deviations from the tool trajectory;
4. development of a predictive model of dynamic changes in the milling process;
5. evaluation of volumetric error and its effect on part accuracy;
6. compensation of volumetric errors through iterative modification of the G-code.

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The evaluation was carried out on the basis of the following main indicators:

- accuracy of abnormal operating mode detection;
- fault detection time;
- equipment downtime level;
- motion accuracy along the trajectory;
- accuracy of regenerative chatter prediction;
- accuracy of volumetric error determination;
- positioning error;
- machining cycle duration;
- energy consumption;
- cutting tool life.

Theoretical Basis and Generalized Model

The forming accuracy of multi-axis CNC machine tools can be expressed in a generalized form as follows:

$$\Delta_f = f(\Delta_d, \Delta_t, \Delta_v, \Delta_h, \Delta_i, \Delta_c)$$

where:

Δ_f - total forming error;

Δ_d - dynamic error in the drive and transmission system;

Δ_t - effect of thermal deformation;

Δ_v - effect of vibrations and chatter;

Δ_h - volumetric error;

Δ_i - deviation along the interpolation trajectory;

Δ_c - residual error after compensation.

The quality of predictive control can be expressed as follows:

$$Q_P = F(D, M, T, H, G, E)$$

where:

Q_P - efficiency of predictive control;

D - diagnostic accuracy;

M - quality of the machine learning model;

T - speed of trajectory deviation detection;

H - degree of volumetric error compensation;

G - efficiency of G-code modification;

E - energy efficiency.

RESULTS.

To compare the effectiveness of the proposed predictive control approach with the conventional method, a comparative analysis was carried out based on the main technological indicators. The results are presented in Table 1.

1-Table.

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Comparative analysis of the main indicators of conventional and predictive control approaches

Indicator	Conventional approach	Predictive control-based approach	Improvement
Accuracy of abnormal mode detection, %	80–85	95–97	+12–17%
Time required for deviation detection, min	15–20	1–2	reduced by 88–93%
Equipment downtime, %	100	85–90	reduced by 10–15%
Motion accuracy along the specified trajectory	Baseline	15–20% higher	+15–20%
Interpolated trajectory deviation detection, μm	Limited / not ensured	5–8	detection capability achieved
Accuracy of regenerative chatter prediction, %	70–75	96	+21–26%
Accuracy of volumetric error evaluation, μm	30–40	15–18	improved by 40–50%
Positioning error, μm	210–220	20–25	reduced by 88–91%
Machining cycle duration, %	100	80–85	reduced by 15–20%
Total energy consumption, %	100	88–90	reduced by 10–12%
Cutting tool life, %	100	135	increased by 35%

A comparative analysis was carried out based on the main technological indicators in order to compare the effectiveness of the proposed predictive control approach with conventional methods. These results are presented in Figure 1..

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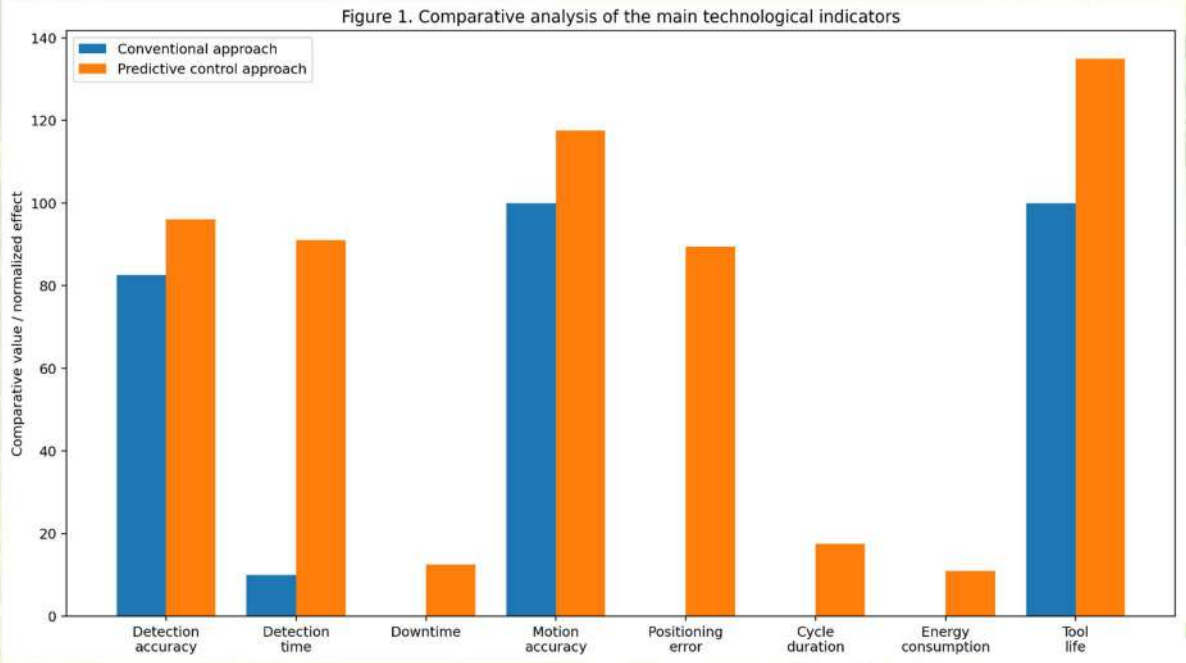


Figure 1. Comparative analysis of the main technological indicators in conventional and predictive control approaches

As can be seen from Figure 1, the predictive control approach provides higher efficiency in the main technological indicators compared with the conventional control approach. In particular, the increase in the accuracy of abnormal mode detection, the sharp reduction in deviation detection time, the improvement in motion accuracy along the trajectory, the reduction in positioning error, the shortening of the machining cycle, the decrease in energy consumption, and the increase in tool life confirm the practical effectiveness of the proposed predictive control system [4].

Intelligent diagnostic system

Software based on machine learning methods was developed and implemented in the control system for intelligent diagnostics using drive current signals. As a result of implementation, the accuracy of abnormal operating mode detection reached 95–97%. The time required for deviation detection was reduced from 15–20 minutes to 1–2 minutes. Due to early fault detection, equipment downtime decreased by 10–15%.

In order to systematize the implemented solutions, their verification methods and obtained results were summarized. These data are presented in Table 2.

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2-Table.

Implemented solutions, verification methods, and obtained results Detection of dynamic errors based on a digital twin

Implemented solution	Verification method	Obtained result
Intelligent diagnostics based on drive current signals	The accuracy of abnormal operating mode detection was evaluated using drive current signals	Detection accuracy reached 95–97%
Intelligent diagnostics	The time required for detecting deviations was compared	Reduced from 15–20 min to 1–2 min
Intelligent diagnostics	Equipment downtime caused by faults was assessed	Downtime decreased by 10–15%
Digital twin of the five-axis CNC machine	The dynamic positioning error of the rotary axis under varying load conditions was calculated	It enabled prediction of dynamic rotary-axis positioning error
Predictive control of tool trajectory deviation	Deviation of the cutting tool from the interpolated trajectory was measured in real time	Deviations of 5–8 μm were detected
Predictive trajectory control	Motion accuracy along complex trajectories was compared	Accuracy increased by 15–20%
Predictive model of milling dynamics	The accuracy of early prediction of regenerative chatter was assessed	Prediction accuracy reached 96%
Volumetric error evaluation method	The spatial error within the working volume was measured	Total spatial error was determined with an accuracy of 15–18 μm
Iterative G-code modification for error compensation	Positioning error before and after compensation was compared	Error decreased from 210–220 μm to 20–25 μm
Intelligent adaptation of machining modes	Machining cycle duration and energy consumption were assessed	Cycle time decreased by 15–20%, energy consumption by 10–12%

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Predictive suppression of vibration and critical loads	Cutting tool life was evaluated	Tool life increased by 35%

A digital twin of the five-axis CNC machine tool was developed, taking into account the backlash in the worm gear pair of the rotary axis, the condition of the bearings, and the thermal expansion of the table housing. This model made it possible to calculate the dynamic positioning error of the rotary axis caused by changes in mechanical loading during machining.

Predictive control of trajectory deviation

A method for real-time calculation and predictive control of the cutting tool deviation from the interpolated trajectory was implemented. As a result, it became possible to detect inter-node trajectory deviations of 5–8 μm, and motion accuracy along complex trajectories was improved by 15–20%.

A comparative analysis based on the main functional indicators was carried out in order to provide an integrated assessment of the effect of the implemented predictive control system on production efficiency. These results are presented in Figure 2.

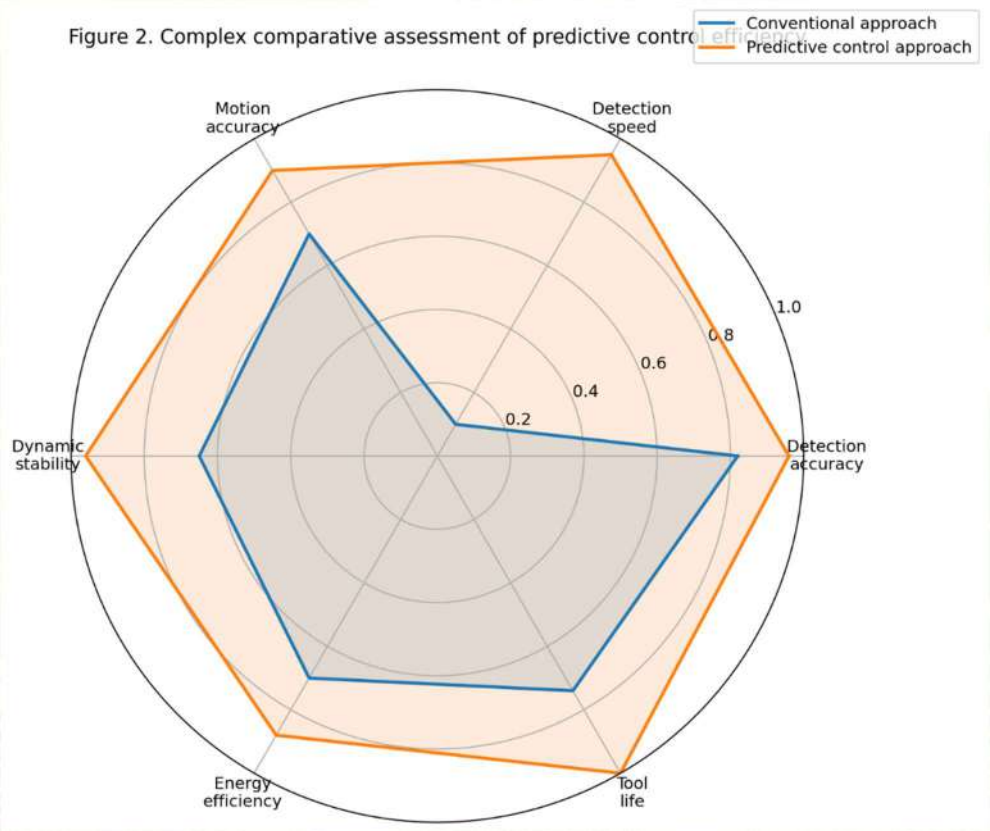


Figure 2. Complex comparative assessment of predictive control efficiency

As can be seen from Figure 2, the predictive control approach demonstrates higher performance than the conventional control approach in terms of diagnostic accuracy, detection speed, motion accuracy, dynamic stability, energy efficiency, and tool life. In particular, a significant advantage is observed in detection speed

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and dynamic stability. This confirms that predictive control in multi-axis CNC machine tools improves not only forming accuracy, but also overall technological reliability and production efficiency [5].

Prediction of regenerative chatter

A predictive model of dynamic changes in the five-axis milling process was developed. This model made it possible to predict the onset of regenerative chatter at an early stage with an accuracy of up to 96%.

Determination of volumetric error

A method for evaluating volumetric error and its effect on part accuracy was developed. As a result, the total spatial error within the working volume of the machine tool was determined with an accuracy of 15–18 μm.

Compensation of volumetric errors based on G-code

A methodology for compensating the volumetric errors of a five-axis machine tool through iterative G-code modification was developed. As a result, the positioning error was reduced from 210–220 μm to 20–25 μm. This corresponds to an improvement in accuracy of 88–91%.

Overall technological efficiency

The developed method and software ensured intelligent adaptation of machining modes in the CNC core. On this basis:

- the machining cycle was reduced by 15–20%;
- total energy consumption decreased by 10–12%;
- motion accuracy along the trajectory was improved to 5–8 μm;
- the cutting tool life was extended by 35% due to predictive suppression of vibration and critical loads.

Discussion.

The obtained results show that improving the forming accuracy of multi-axis CNC machine tools is ensured not by improving only one factor, but by managing diagnostics, the digital twin, trajectory control, prediction of dynamic processes, and compensation of volumetric errors as a unified system.

First, the possibility of detecting abnormal operating modes with high accuracy on the basis of drive current signals made it possible to assess the technical condition of the equipment in near real time and to identify faults at an early stage. This reduced downtime and improved overall production efficiency.

Second, the implementation of the digital twin made it possible to predict the actual dynamic state of the machine tool and its response to mechanical loads. In particular, taking into account backlash in the rotary axes and thermal expansion became an important factor in high-precision machining.

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Third, the detection of deviations along the interpolated trajectory at the level of 5–8 μm and the improvement of motion accuracy by 15–20% confirmed the practical effectiveness of the predictive control system. In machining complex spatial surfaces, this indicator is one of the key factors determining forming accuracy.

Fourth, the possibility of predicting regenerative chatter with an accuracy of up to 96% made it possible to suppress vibrations in advance and prevent critical loads. This had a positive effect not only on part quality, but also on tool life and process stability.

Fifth, the iterative compensation of volumetric errors based on G-code reduced the positioning error from 210–220 μm to 20–25 μm. This result shows that the combined application of predictive control and compensation significantly improves accuracy in multi-axis CNC machine tools.

In general, the "diagnostics – prediction – digital twin – compensation – intelligent adaptation" chain proved to be a scientifically grounded unified system for controlling the forming accuracy of multi-axis CNC machine tools.

CONCLUSION.

Under technological loads, the forming accuracy of multi-axis CNC machine tools is directly determined by dynamic, thermal, trajectory-related, and volumetric errors. The implementation of an intelligent diagnostic system based on drive current signals made it possible to detect abnormal operating modes with an accuracy of 95–97%. The calculation of dynamic errors of the rotary axis based on a digital twin made it possible to predict the behavior of the machine tool under real operating conditions. As a result of predictive control of deviations along the interpolated trajectory, motion accuracy was improved by 15–20%, and deviations at the level of 5–8 μm were detected. The possibility of predicting regenerative chatter in the milling process with an accuracy of up to 96% increased process stability. The compensation methodology based on iterative G-code modification reduced the positioning error from 210–220 μm to 20–25 μm. The integrated application of intelligent adaptation, predictive control, and compensation reduced the machining cycle by 15–20%, decreased energy consumption by 10–12%, and extended tool life by 35%. Predictive control in multi-axis CNC machine tools is a scientifically and practically promising direction for improving forming accuracy.

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