Research Status and Development of Precision Analysis of CNC Machine Tools

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Abstract. Accuracy is a key quality characteristic of CNC machine tools, reflecting the pros and cons of machine tool performance. Accuracy is affected by performance failures of CNC machine tools, such as vibration, friction, and heat transfer. Therefore, it is difficult to accurately model and comprehensively analyse the accuracy of the machine tool by studying the influence of certain factors on the accuracy of the CNC machine tool in isolation, which makes it difficult to find out the problems in the design or manufacturing process. The article analyses the current status and research significance of domestic CNC machine tool accuracy, expounds the domestic and foreign research status of CNC machine tool accuracy modelling method and CNC machine tool accuracy comprehensive analysis, summarizes the existing problems and development trends of CNC machine tool accuracy research, and compares it based on the meta-action. The theoretical systematic modelling of the accuracy of CNC machine tools and the key issues of comprehensive evaluation of the accuracy of CNC machine tools combined with the meta-action chain provide insights and provide analytical methods for the design and manufacture of CNC machine tools.

1. Introduction
As the industrial mother machine of the equipment manufacturing industry, CNC machine tools are the core equipment for high-efficiency processing of high-precision complex parts. Its manufacturing level and quality are the key to the strength of a country. Future manufacturing development requirements are low manufacturing costs, high precision, high product quality, flexible manufacturing methods, green manufacturing, etc. [1]. As an important support for the modern manufacturing industry, CNC machine tools will focus on improving their machining accuracy, product quality, work efficiency, and intelligent digitalization in the future. At present, my country’s high-end products, such as precision CNC machine tools, can only be produced by a very small number of companies, and most of the CNC machine tool companies focus on low-end products. The product technology level is relatively low, and high-end CNC machine tools need to rely on imports. The main reason for the current status quo is that the technical level of the quality design of CNC machine tools in my country is relatively backward compared with developed countries, and the quality (such as accuracy) of CNC machine tools is first designed. In order to realize the transition from "Made in China" to "Intelligent manufacturing in China", it is urgent to start with quality, especially in accelerating innovation in the
quality design technology of CNC machine tools, such as precision and reliability design technology. The quality level of machine tools has been upgraded to a higher level, which further strengthens the competitiveness of Chinese manufacturing [2].

The traditional design steps of CNC machine tools are mainly divided into three steps: one is the overall design of the CNC machine tool, the second is the detailed design of the parts of the CNC machine tool, and the third is the comprehensive evaluation and inspection of the whole CNC machine tool. Among them, the necessary analysis in the overall design is crucial, which can greatly reduce the cost and difficulty of the machine tool development process. Therefore, it is necessary to perform an efficient and accurate precision analysis of the machine tool, but the current research and analysis are generally for the whole machine or parts, which ignores the characteristics of the machine tool depending on the motion to determine the function, and an analysis method based on the motion is urgently needed. With the rapid progress of society and the rapid development of science and technology, for machine tool companies, users will put forward higher and higher requirements for the accuracy of CNC machine tools. In order to gain greater market competitiveness for machine tools, companies must also improve their product analysis capabilities while designing and developing high-precision CNC machine tools. Therefore, studying the accuracy of CNC machine tools, especially accuracy modeling and comprehensive analysis methods, has great theoretical significance and practical value for the design and manufacture of machine tools.

1.1. Accuracy modelling method of CNC machine tools
Regarding the analysis of machine tool accuracy, it is mainly to analyze static accuracy and dynamic accuracy [3]. Scholars at home and abroad have done a lot of research on static accuracy, and made great progress. At present, many static precision modeling methods have been formed, which are mainly divided into multi-body kinematics method, mechanism modeling method, error matrix method and rigid body kinematics method.

The process of forming a machine tool product is a relatively complex manufacturing process involving multiple processes. In this manufacturing process, each of the sub-process influencing factors and accuracy formation must have mutual influences between accuracy characteristics relationship. Therefore, Yan et al. [4] analyzed because of the influence of the shape of the mating surface, when two parts were assembled, on this basis, they established a multi-body system theory-based multi-mechanical assembly process error transfer model, and determined each component. The impact of geometric errors on assembly accuracy and key issues such as the assembly process. In order to study the coupling mechanism of assembly errors, Liu et al. [5] established the assembly accuracy transfer function based on the state-space model. Zhou et al. [6] established an error transfer model and quality assessment method based on the assembly sequence. According to the assembly relationship matrix and the tolerance relationship matrix, an error transmission path is automatically formed, and then the cumulative error of the assembly is solved through the error transmission path to complete the calculation of the assembly accuracy. Li et al. [7] used the error transmission link diagram and the link network diagram to intuitively establish the transmission path of the assembly error, analyzed the assembly error according to the theory of the meta-action assembly unit, and proposed an assembly error analysis method based on the model of the meta-action assembly unit. Kang et al. [8] and Yang et al. [9] studied the machining process of a specific machine tool, combined with multi-body kinematics theory, established a unified error model based on the homogeneous coordinate matrix transformation method, and deduced the transfer function of terminal error. Liu et al. [10] considered the processing characteristics of parts, processing elements and node factors, and constructed a three-dimensional network model of process flow error transmission. Zhang and Ran et al. [11] proposed the comprehensive error prediction method for multi-process processing based on the error transmission mechanism.

In addition, with the development of CNC machine tools in the direction of high precision, high precision and intelligence, domestic and foreign scholars have also conducted a lot of research on its dynamic error. Chen et al. [12] considered the relative displacement error between the machine tool
and the workpiece, established a kinematics model. They also tried to compensate for the non-rigid body error, and comprehensively considered 32 different error components, and established a model of geometric and thermal errors using the standard homogeneous coordinate transformation method, and this error compensation model method has also achieved good results. Ramesh [13] studied the law that the dynamic performance of the machine tool servo control system has an influence on the contour error, and proposed a fuzzy inference coupled contour error compensation mechanism, which greatly improves the machining accuracy of the machine tool. Li et al. [14] used the AFSA-ACO-BPN algorithm to construct a dynamic model of a five-axis machine tool, predicted the machining accuracy of the five-axis machine tool, and conducted experiments to verify the correctness of the model.

1.2. Comprehensive analysis method for the accuracy of CNC machine tools

In order to improve the efficiency of machine tool accuracy design, Wang et al. [15] proposed a machine tool accuracy design scheme based on the combination of error prediction and digital methods, which provided theoretical guidance for machine tool design accuracy. Pang et al. [16] analysed the error sources and influencing factors of the CNC machine tool measurement system, used PSO-SVM and BP neural network algorithms to establish a prediction model for the dynamic positioning error of the XY table, and developed the XY table for further verification. The correctness of the established model. Moon et al. [17] analysed the motion structure of the machine tool based on the spin theory, and established a five-axis CNC machine tool geometric error prediction model and approximate compensation model using the spin theory. Gao et al. [18] established the machining error model of the entire machine tool based on the Jacobian transfer matrix, and proposed a continuous error prediction method for the machining space of the machine tool. Luo, H.L. [19] integrated the error source and error transmission of mechanical products, established an error transmission state space model based on key points, determined the calculation method of assembly accuracy and reliability, and was based on Visual Studio, Qt, Creo and Matlab and other platforms have developed software for evaluating the reliability of the accuracy of mechanical product assembly.

2. Analysis of existing problems and development trends

From the above research status at home and abroad, it can be seen that the dispersion and locality of the current research on the accuracy of CNC machine tools are more obvious.

2.1. The specific problems

2.1.1. The precision modelling method does not fully reflect the characteristics of "motion" and "action". The main functional characteristics of machine tool products are reflected in the motion of parts. The motion of the components is completed by the power source through a series of internal motion units under the transmission of force or torque. A complete transmission chain is formed from the power source to the components, and the motion of each transmission part in the transmission chain is the most basic form of motion for machine tools. To ensure the improvement of the overall accuracy of the machine tool, it is necessary to ensure the stable operation of each motion unit. Therefore, the starting point for accuracy modelling of machine tool products should be the motion unit rather than a single component. The modelling process should fully reflect the interaction of each component in the motion unit, such as force, moment, friction, vibration, etc. Regardless of whether it is static modelling or dynamic modelling, most of the current domestic researchers' accuracy analysis and modelling methods of CNC machine tools are concentrated on the whole machine, which is basically carried out on the parts of its structure, that is, according to the "integration" method. The decomposition method of "machine-component-part" researches and analyses the whole machine, and studies the mapping relationship between the machine tool space error and the machine tool parts error. It is not based on the basic characteristics of machine tool product "motion", and it does not consider the influence of dynamic factors, and cannot reflect the relative motion relationship of parts, transmission accuracy and force transmission.
In the traditional precision design analysis, the parts are generally regarded as a whole motion, so as to model based on the parts. However, the granularity is too coarse to penetrate into the machine structure, which is not conducive to the realization of more detailed analysis. The assembly analysis is generally aimed at the assembly process of the parts, so the granularity of the part-based modelling method is too fine. When the number of parts is too large, the modelling and analysis will be very cumbersome. The machine tool product realizes various functions of the whole machine according to the relationship of "action-motion-function" through the interaction between parts and components, and also determines various performances. It is necessary to model from the action level. Therefore, the characteristics of "action" and "motion" must be reflected in the process of precision modelling.

2.1.2. Lack of a mature and systematic comprehensive analysis method for the accuracy of the whole machine.

At present, domestic and foreign scholars have done more research on comprehensive analysis and prediction of accuracy, including the design, manufacturing, assembly and operation of CNC machine tools. In the modelling process of accuracy synthesis, most of them just built error models, and failed to analyse the error sources that produce errors, and failed to find out the key error sources that affect the accuracy of the machine tool. Even if the related error sources were traced, its modelling was carried out at the level of the whole machine or component, and the error source involved is more cumbersome. In addition, the impact of machine tool performance on accuracy cannot be ignored, such as vibration and heat transfer. Most researchers studied the impact of certain factors on the accuracy of CNC machine tools in isolation, so that they could not accurately perform comprehensive modelling and analysis on the accuracy of the machine tools, and the evaluation results obtained could not be completely consistent with the actual situation.

2.2. Development Strategy

2.2.1. Systematic modelling method of CNC machine tool accuracy based on meta-action theory.

Traditional precision modelling methods of CNC machine tools are mostly based on the overall modelling of the whole machine or parts, and the decomposition method of "function-motion-action" (FMA) can be adopted to decompose the motion functions of CNC machine tools to the smallest motion level, Meta-actions. Moreover, analyse the error mechanism at this level, and conduct dynamic modelling and simulation of common meta-actions. In the meta-action theory, all the parts related to the realization of a meta-action are regarded as a whole, which is called the meta-action unit. The relevant analysis is carried out on the meta-action unit. Structurally speaking, the meta-action unit is an intermediate structure between parts and components. It acts as a medium for part and component analysis, which not only avoids the cumbersomeness of part-based analysis, but also breaks the roughness of component-based analysis.

According to the FMA decomposition tree, as can be seen from Fig.1, an error model is established for a target meta-action, and the performance impact of meta-actions from different meta-action chains is analysed to find out the specific error source. The specific analysis is divided into: (1) Analyse the coupling mode between different chains and adjacent element actions to the target element action accuracy. According to the error sources in the motion process, such as wear, temperature, deformation, friction, vibration, etc., different coupling modes of meta-action accuracy can be established. (2) Analyse the reason and mechanism of coupling of meta-action accuracy. For the coupling mode obtained in (1), the coupling reason and coupling mechanism under each coupling mode are analysed. The coupling reason is analysed from the connection mode between adjacent elementary action units in different chains, such as structural coupling and spatial coupling. Coupling (there are geometric constraints or position constraints between the two elementary action units), etc. (3) Establish accuracy calculation models under different coupling modes. For different coupling modes, the accuracy model of the target meta-action is established, and the specific influence value is solved. (4) Synthesize model that integrates all possible coupling modes. Considering the influence
values of different coupling modes, the ones with greater influence need to be assigned with larger weights. These results are then combined to establish a total accuracy coupling calculation method.

\[ \text{Fig. 1 FMA structural decomposition model of CNC machine tool} \]

2.2.2. Comprehensive analysis of the accuracy of CNC machine tools combined with meta-action chain. The function and performance of the whole machine are jointly realized and guaranteed by many transmission chain-type structure of the element action unit. After the error transfer model between the two element actions is established, the accuracy of the element action needs to be integrated into the accuracy of the whole machine. Synthesis is the reverse synthesis along the meta-action chain in the FMA tree, that is, the comprehensive analysis model of the accuracy of CNC machine tools is constructed based on the performance characteristics of each element-action chain of the meta-action unit. A systematic comprehensive method for the accuracy of CNC machine tools is formed to solve the problem of numerical control. The error source of the machine tool is difficult to trace, the modelling granularity is coarse, and the model is inaccurate. The comprehensive method can refer to the quantitative analysis method of the fault tree, establish the comprehensive equation of accuracy and quality characteristics, and carry out the synthesis and analysis of the accuracy of the machine tool step by step.

Finally, the comprehensive results need to be verified and evaluated, and mathematical statistics techniques are used to determine the confidence of the overall accuracy evaluation results. Then compare the evaluation results with the design accuracy of the product. If the analysis accuracy of the product is better than the design accuracy, the entire analysis work ends here. Otherwise, it is necessary to feed relevant issues back to the designer, modify and optimize the design plan, and then perform the next round of analysis on the optimized design plan.

3. Conclusions
With the rapid progress of society and the rapid development of science and technology, people are paying more attention to the accuracy of CNC machine tools, and more and more researches are being carried out. Precision analysis is a crucial link in the design of machine tools. It is difficult to accurately model and comprehensively analyse the accuracy of machine tools by studying the influence of certain factors on the accuracy of CNC machine tools in isolation, so it is difficult to find problems in the design or manufacturing process. Therefore, the article clearly analysed the current status of the accuracy of CNC machine tools at home and abroad, understood its research significance,
and studied the precision analysis of the design process of CNC machine tools based on the meta-action theory to improve the better development of the precision design of domestic CNC machine tools.

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