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A new approach to improving the machining precision based on dynamic sensitivity analysis

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ABSTRACT

This paper proposes a new approach to improving the machining precision based on dynamic sensitivity analysis. Firstly, the movement transmission chain of machine tools is analyzed to establish the error propagation model. The model can be used to calculate the error sensitive coefficient of each component. Secondly, the deformation of each component is acquired depending on the finite element analysis. Combining the error sensitive coefficient and deformation, the sensitive error components of machine tools are identified. Thirdly, according to the sensitive error components, the layout of the machine tool is modified and the stiffness of sensitive error component is improved to reduce the machining error of machine tools. A simulation example about globoidal cam machine tools is conducted. Comparing the machining error of vertical globoidal cam machine tool and horizontal globoidal cam machine tool in the simulation, the feasibility of the method is verified. This method not only increases the stiffness of the sensitive error component, but also changes the layout of the machine tool based on dynamic sensitivity analysis results. Therefore, it can provide a new approach to improving the machining accuracy. Finally, an experiment was conducted to verify the validity the correctness of the conclusions.

1. Introduction

With the growth of the demand for high performance machine tools, how to improve the performance of machine tools has become a research topic. The performance mainly includes the dynamic response characteristics, the whole machine tool weight, the stiffness of a machine tool and the machining error. Some studies have been carried out for improving the machine tool performance. Li et al. [1] conducted the experimental modal analysis and operational modal analysis to estimate the modal parameters of machine tools at different feed speeds. Mao et al. [2] proposed a random decrement technology-based analysis method to identify the operational modal parameters of machine tools without the any knowledge about input forces. The two methods above provide a powerful tool for improving the dynamic performance of a machine tool. Li et al. [3] proposed the topology optimization method of machine tool weight according to the load bearing of machine tools bed. It can not only reduce the weight of machine tools, but also ensure the strength. Li et al. [4] introduced a new approach for designing the stiffener layout inside large machine by a biologically inspired topology optimization method according to the plant leaf vein structure. The optimization method was validated by a machine tool column experiment. Wang et al. [5] establish a dynamic model of a three axis gantry milling machine tool with considering the axis coupling effects. Based on the dynamic model, the effect of axis coupling force on the stiffness changes of kinematic joints is analyzed, and the variations of the frequencies and frequency response functions with position parameters are calculated. In order to minimizing the weight of a machine tool while maintaining sufficient stiffness of the machine tool, Wu et al. [6] propose a modified two-level optimization approach for the concept design of a machine tool. The method above can improve the performance of a machine tool in different sides, and they all achieved good results. The quality of products is determined by the machining precision, so the machining accuracy is the most important criterion of a machine tool.

Machining accuracy is an important criterion for assessing the machine tools performance. Lots of researches have been carried out to investigate the machining error causes and elimination methods. Factors that affect the machining accuracy mainly include the geometric errors, deformation errors of cutting force, assembly errors of machine tool components, and thermal deformation errors [7,8]. Tian et al. [9] established a geometric error model to explore the precision design and error compensation of machine tools. Moreover, some researchers [10–12] built the dimensional geometrical error model of machine tools, and analyzed

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the machining precision based on the geometrical error model. Zuo et al. [13] presented an integrated geometric error model of machining system and compensation method on machine tools to realize the identification of error components and the compensation of machining error. Wang et al. [14] developed a machine tool equipped with counter balance axes, to achieve high acceleration/deceleration without causing any vibration. The method can make the machine tools have a high precision. Narendra Reddy et al. [15] presented a real-time compensation method for thermal error. The thermal error compensation method regarded the temperature as input parameters to calculate deformation and compensation based on artificial neural network. Finesa and Agahb [16] used artificial neural network to predict the compensation amount for compensating the machine tool positioning error.

However, the calculation process about error compensation is very complex. It is not suitable for real-time machining process. Moreover, error compensation needs expensive measurement devices and controllers, so it increases the manufacturing costs. Therefore, this paper proposes a new approach to improving the machining procession based on dynamic sensitivity analysis. Because the machining process is dynamic, the machining error model will change with the change of the cutting position, and the machine tool will have a dynamic deformation caused by the dynamic cutting force. Aiming at the different cutting positions of a workpiece, the dynamic error propagation model is established, and the error sensitive coefficients at different working points are calculated. In addition, according to the dynamic change of cutting force, the deformation analysis of each component is conducted to acquire the workpiece deformation in different cutting positions. Combined the dynamic error sensitive coefficients and the dynamic deformation, the sensitive error components of machine tools are recognized. Finally, in order to reduce machining error, the layout of the machine tools is modified and the stiffness of sensitive error component is improved. Compared with the conventional error compensation method, the presented method has the following advantages. (1) Changed the machine tool layout and increasing the stiffness of sensitive error components can be done at the beginning of machine tools design. This method can provide the theoretical basis in high precision design of machine tools to reduce the machining error and manufacturing costs. (2) The proposed method can not only reduce deformation error by increasing the stiffness of sensitive error components, but also decrease the sensitive coefficients by changing the layout of machine tools.

Globoidal cam is one of most important mechanisms in mechanical automation field. Because the globoidal cam has the advantage of small noise and dividing precision, it is usually used as a dividing mechanism of machine tools. Some research about the globoidal cam has been carried out. Lo et al. [17] have done some research on the bearing contact of globoidal cam, so the contact nature and the contract stress of the globoidal cam can be analyzed. Chang et al. [18] proposed a generalgeometry design method for the globoidal cam, and the outline equation of globoidal cam was deduced. Moreover, the globoidal cam is difficult to machine, so the machining accuracy is very important to evaluate the machining quality of a globoidal cam. Ji et al. [19] carried out a research on the rib-thickness calculation of a globoidal cam. It can be used to predict the peak value of the velocity. Kuang et al. [20] proposed a torque compensation mechanism to evaluate the dynamic behavior of the globoidal cam. However, the quality of a globoidal cam must rely on the machine tool. Therefore, the globoidal cam machine tool is used to conduct the experiment.

2. The component error and machining error of machine tools

2.1. The component error of machine tools

In general, a component of machine tools exists six types of errors, which are three types of linear errors and three types of rotation errors respectively. Assumes that the theoretical correct coordinate system of the ith component (such as processing cutting tool) is $o_ix_iy_iz_i$, and the error coordinate system of the ith component is $o_i'x_i'y_i'z_i'$ relative to workpiece coordinate system $oxyz$. The linear errors of the ith component are δx_i, δy_i, δz_i respectively, and the rotation errors of the ith component are $\delta\alpha_i, \delta\beta_i, \delta\gamma_i$ respectively. In this paper, only deformation error of a component is considered. The component error of a machine tool is shown in Fig. 1.

Because the rotation errors are small, the $\sin(\delta\alpha_i) \approx \delta\alpha_i$, $\sin(\delta\beta_i) \approx \delta\beta_i$, $\sin(\delta\gamma_i) \approx \delta\gamma_i$, $\cos(\delta\alpha_i) \approx \cos(\delta\beta_i) \approx \cos(\delta\gamma_i) \approx 1$, The error matrix of the ith component can be written as:

$$T_i^e = \begin{bmatrix} 1 & -\delta\gamma_i & \delta\beta_i & \delta x_i \\ \delta\gamma_i & 1 & -\delta\alpha_i & \delta y_i \\ -\delta\beta_i & -\delta\alpha_i & 1 & \delta z_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

2.2. The machining error of machine tools

The actual contour point and the theoretical contour point of workpiece can't completely overlap because of the existence of machining error of machine tools. Assumes that the theoretical contour point is $C^T = \{x\ y\ z\ 1\}^T$, and the actual contour point is $C'^T = \{x'\ y'\ z'\ 1\}^T$. So the workpiece error is defined as the difference between theoretical contour point and actually contour point:

$$\Delta C^T = C'^T - C^T = \{x'\ y'\ z'\ 1\}^T - \{x\ y\ z\ 1\}^T \tag{2}$$

The error in workpiece normal direction has the biggest influence on machining accuracy, so the sensitive direction of

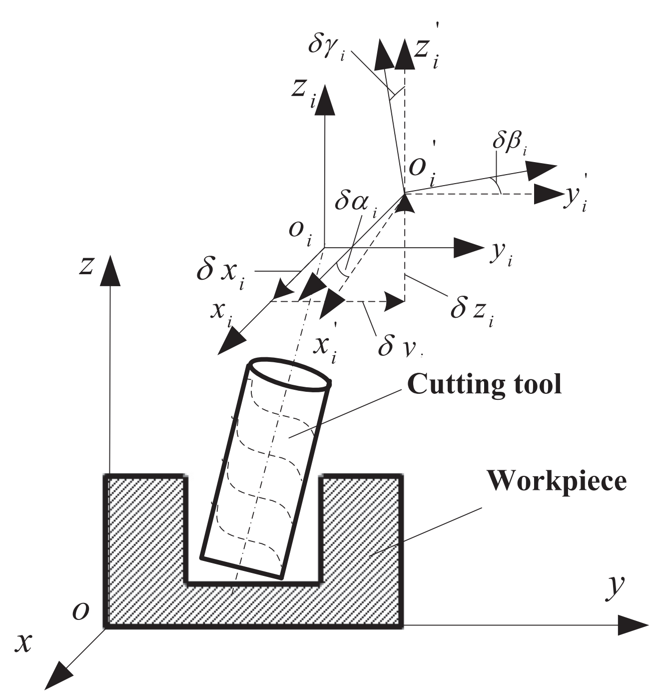

Fig. 1. The component error of machine tools.