Method of Tolerance Design and Verification of Parts Based on Follow-up Crankshaft Grinder with Following Double Grinding Wheel Frame

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Abstract. Calculating the parameters of accuracy along each axis by the comprehensive geometric accuracy and then optimizing as well as assigning the accuracy, which is the cutting-edge way of accuracy design of machine tools. However, the guarantee of the comprehensive geometric accuracy of machine tools is ultimately to implement the tolerance of specific moving parts. In view of the present shortage about accuracy design of machine tools, this paper puts forward to a way to design and verifies the tolerance of movement parts based on the comprehensive geometry precision of K2-1080 Crankshaft Grinder with Following Double Grinding Wheel Frame.

Key Word: crankshaft grinder; geometric accuracy; precision design; tolerance design.

1. Introduction
Crankshaft Grinder with Following Double Grinding Wheel Frame have many motion pairs as well as long kinematic chains, and their comprehensive stiffness and accuracy are easily affected [1]. When compensating the comprehensive errors of Crankshaft Grinder with Following Double Grinding Wheel Frame, it is necessary to measure the errors of machine tools along the direction of each axis, which is more difficult in the actual error compensation of Crankshaft Grinder with Following Double Grinding Wheel Frame. Because tolerances are used to limit errors, the comprehensive geometric errors of machine tools are solved by superimposing random geometric errors of each pair of motion.

Therefore, the geometric tolerance analysis model of five-axis machine tools can be established by giving the geometric tolerance terms of the parts and components of each moving pair to cover the geometric errors in each axis direction. Combined with the randomness of the comprehensive geometric errors of Crankshaft Grinder with Following Double Grinding Wheel Frame, the Monte Carlo simulation method is used to simulate and analyze the three-dimensional errors, so that the final design of the comprehensive geometric accuracy of five-axis machine tools can be achieved. Combining with the randomness of the comprehensive geometric error of five-axis machine tools, the Monte Carlo simulation method is used to simulate and analyze the three-dimensional error, which makes the design of the comprehensive geometric accuracy of Crankshaft Grinder with Following Double Grinding Wheel Frame fall on the geometric tolerance of the components that make up the specific motion pairs...
The direction of comprehensive error compensation for Crankshaft Grinder with Following Double Grinding Wheel Frame provides a favorable basis.

2. Design of Comprehensive Geometric Accuracy for Crankshaft Grinder

2.1. Geometric Error Term of Crankshaft Grinder

For crankshaft grinder, there are three axes moving parallelly along X, Y and Z directions, each axle will produce three-line displacement errors along X, Y and Z directions, three-line displacement errors around X, Y and Z directions, and three-line displacement errors along X, Y and Z directions of two rotating axes C1C2 and three-line displacement errors around X, Y and Z directions. In addition, there are three verticality errors between the three linear motion axes. These three verticality errors do not change with the movement of the moving body of the machine. There are 33 geometric errors in the crankshaft grinder. As shown on figure1.

Taking the shifting axis as an example, there are six errors in the movement of the machine tool table along the guide rail, namely three displacement errors and three angle errors. Take X-axis translation motion as an example. There are three translation errors, namely, delta x (X), delta y (X), delta Z (X), and three angular errors, namely, delta x (X), delta y (X), delta Z (X), and three angular errors, namely, delta x (X), delta y (X), and delta Z (X). Delta represents displacement error, epsilon represents angle error, letters in parentheses represent direction of motion, letters in subscripts represent direction of error.

Similarly, the errors of translation along the Y axis are: delta x (Y), delta y (Y), delta Z (Y), delta x (Y), delta y (Y), delta Z (Y). The errors of translation along Z axis are: delta x (Z), delta y (Z), delta Z (Z), delta x (Z), delta y (Z), delta Z (Z).

2.2. Geometric Tolerance Term Control of Motion Parts

Assuming that M is a point on the worktable, because of the existence of both straightness and angle errors. It can be seen that M still fluctuates within a certain limit and does not exceed that limit. This is similar to the concept of contour error in dimensional tolerance.

Figure 1. K2-1080 Crankshaft Grinder with Following Double Grinding Wheel Frame

According to the above analysis, when the slider moves along the X-axis direction, due to the existence of straightness error and angle error of the guideway, the worktable moves and twists in a certain range of the XY plane and YZ plane. Therefore, for the planar guideway, it can be converted into the surface profile and verticality of the contact surface. Given the flatness of the contact bottom surface, it can cover delta y (X), delta x (X) and delta y (X), and the verticality of the two contact sides can cover delta Z (X) and delta y (X); For cylindrical guideways, it can be transformed into the straightness and side verticality of V-type guideways. Given the position degree of the axis of V-type guideway, it can cover delta Z (X), delta x (X) and delta y (X), side verticality can cover delta y (X), delta Z (X), and delta x (X) is limited by the accuracy of servo motor along the X axis of machine tool. The initial values of surface contour and verticality are as follows: The factors influencing the flatness of the bottom surface are as follows: delta y (X), delta x (X) and delta y (X).

The resulting flatness magnitude $\Delta_a$ is shown in the formula (1):
\[ \Delta_a = \delta_y(X) + \sin(\varepsilon_y(X)) \cdot \frac{L_{aX}}{2} + \sin(\varepsilon_x(X)) \cdot \frac{L_{aY}}{2} \]  

(1)

The influence factors of lateral verticality are as follows: delta \( Z(X) \) and delta \( x(X) \). The magnitude \( \Delta_b \) of verticality caused by delta \( Z(X) \) and delta \( x(X) \). See formula (2):

\[ \Delta_b = \delta_z(X) + \sin(\varepsilon_z(X)) \cdot \frac{L_{aX}}{2} \]  

(2)

\( L_{aX} \) and \( L_{aY} \) respectively indicate the length of the worktable and the machine tool guideway in the X and Y directions, and the angle is radian. The analysis process of the position degree of the cylindrical guideway axis is similar to that above.

2.3. Establishing Geometric Tolerance Model of Machine Tool

In the computer aided tolerance simulation analysis software, the dimension chain is a geometric tolerance model, which is obtained by superimposing geometric tolerances on the components of each moving pair. Therefore, when analyzing the comprehensive geometric errors, it is necessary to convert the geometric errors into the geometric characteristic tolerances of the machine tool assembly parts [5]. This paper takes K2-1080 Crankshaft Grinder with Following Double Grinding Wheel Frame as an example. When building the geometric tolerance analysis model of machine tools, we only consider important parts (such as moving parts) and ignore most of the strengthening parts (such as standard parts). For the parts that constitute the moving pair, the motion errors along the moving direction are limited by the given flatness and verticality of the contact characteristics of the two parts assembly; for the moving pair composed of cylindrical guides, the position of the cylindrical axis needs to be given. [6]. The vertical and parallel errors between the moving directions of the machine tools along the axes require the tolerances of the assembly features and the parallelism of each other to be constrained jointly. Through the above conversion of geometric errors, assembly is carried out according to the actual assembly sequence of machine tools, so the geometric tolerance analysis model of K2-1080 Crankshaft Grinder with Following Double Grinding Wheel Frame can be established. As shown on Figure 2.

Figure 2. Frequency distribution histograms of b and c.

3. Comprehensive Geometric Error Analysis

The common methods of tolerance analysis are extreme value method, statistical tolerance method and Monte Carlo method.

The principle of extremum method is simple and the calculation is small. It does not need to consider the size distribution of parts in the tolerance zone. It can guarantee the success rate of assembly and the interchangeability of parts to be 100%. But the design is too conservative, which increases the processing cost. Statistical tolerance analysis method is to describe the change of part size in the form of statistical distribution, and calculate the statistical distribution of part manufacturing capacity and assembly function [7]. This method assumes that the tolerance of parts obeys normal distribution, and the relationship between assembly tolerance and part tolerance is linear. The results are not completely consistent with the actual situation. Monte Carlo method treats the problem of finding the size and tolerance of a closed ring as a statistical problem of finding a random variable. According to the actual distribution of each dimension, a certain algorithm is used to sample in the computer, generate the corresponding random number, and calculate the size and tolerance of the closed ring according to the
design function. Under certain conditions, the results obtained by this method are in good agreement with the actual situation.

According to the nature of the synthetic geometric errors of Crankshaft Grinder s, it is based on the structure of Crankshaft Grinder, and the random geometric errors of each pair of motion are transformed and solved. It uses the statistical method of random variables to solve the size and tolerance of the closed loop. The tolerance is a variable with random distribution and limited in a certain range. Its property is consistent with the geometric error of the Crankshaft Grinder l. Therefore, Monte Carlo simulation method can be used to simulate and analyze the three-dimensional geometric errors of Crankshaft Grinder. At present, there are many mature tolerance simulation software using Monte Carlo simulation method, among which Vis VSA developed by Siemens Company is mainly used for spatial dimension chain operation. The assembly errors of Crankshaft Grinder are analyzed by the computer-aided tolerance analysis software Vis VSA. The most important contributing factor to the target size can be found out, and the corresponding parts tolerances can be rationally modified according to the analysis results [8]. On the one hand, the three-dimensional tolerance simulation design verification based on the requirements of the comprehensive geometric accuracy of Crankshaft Grinder can be realized, so that the guarantee of the comprehensive geometric accuracy of Crankshaft Grinder can be realized on the tolerance of each component of the specific motion pair; at the same time, the contribution factor can be used to provide a favorable basis for the follow-up comprehensive error compensation direction of Crankshaft Grinder. On the other hand, the ability to meet the processing quality and the quality stability of products can be evaluated according to the CP and Cpk in the report. In the past research of precision design, the design goal is usually to optimize the accuracy of the whole machine or to minimize the cost [9]. For the precision design of precision horizontal machining centers, we often do not seek some optimal solutions, but to obtain a set of optimal solutions satisfying certain conditions [10]. Using MATLAB to solve the above optimization problems after 48 iterations, the optimal and design values of design variables and the upper bound of the corresponding attitude error range of each axis moving component are obtained as shown in Table1.

Table 1. Results of the optimal error assignment.

| Item                          | Accuracy Optimization and Allocation Results of Design Variables |
|-------------------------------|---------------------------------------------------------------|
| Installation Error of Guide Rail | X₁   | X₂   | X₃   | X₄   | X₅   | X₆   |
| Optimized Value               | 4.0254 | 4.9425 | 4.2987 | 9.8535 | 4.6237 | 4.2375 |
| Design Value                  | 4      | 5     | 4     | 10    | 5     | 4     |
| Trailer Attitude Error        | ε₁(ₓ)  | ε₁(ᵧ)  | ε₁(𝑧)  | ε₂(ₓ)  | ε₂(ᵧ)  | ε₂(𝑧)  |
| Optimized Value               | 2.755  | 6.405  | 5.124  | 22.39  | 12.77  | 8.956  |
| Design Value                  | 3      | 6     | 5     | 22    | 13    | 9     |

According to the results of tolerance allocation, 10 000 simulation points are randomly selected in the workspace of machine tools. At each simulation point, a group of manufacturing and installation errors of guideways satisfying tolerance requirements are randomly generated. The position errors of tool relative to workpiece are calculated. Finally, the position errors of x, y and Z directions and corresponding volume errors are obtained. It can be seen that the probability of the position errors of the x, y and Z directions of the end of the machine to meet the design targets is 99.12%, 99.02% and 98.96%, respectively. The rationality of the tolerance design values of the machine tool and the validity of the precision design method are verified. As shown on figure 3.
4. Conclusion

The three-dimensional tolerance design verification based on the requirement of the comprehensive geometric accuracy of Crankshaft Grinder is realized. By modifying the corresponding parts tolerance reasonably through the contribution factor, the guarantee of the comprehensive geometric accuracy of Crankshaft Grinder can be realized on the tolerance of each part of the specific motion pair. Available contribution factor can provide a useful basis for the direction of comprehensive error compensation of follow-up Crankshaft Grinder. The error sensitivity analysis model of NC machine tools based on interval analysis theory is established. On this basis, the global maximum sensitivity index is defined to quantitatively describe the above-mentioned influence degree. At the same time, it provides a theoretical basis for the follow-up precision design. The error mapping model between manufacturing and installation errors of guideway and six-dimensional pose errors of moving parts is established. The statistical mapping rules between the two are analyzed by Monte Carlo simulation algorithm, and empirical formulas are formed. It is used to guide the distribution of installation tolerance in subsequent rail manufacturing.

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References

[1] Li Ming, Felina. Geometric coordinate measurement technology and its application [M]. Beijing: China Quality Inspection Press, China Standard Publication, 2012.

[2] Jiang Qianqian. Theory and Application of New Generation GPS Standard [M]. Beijing: Higher Education Press, 2007.

[3] Lu Qiang, Zhang Youliang. Precision synthesis of 6-leg parallel machine tools by Monte Carlo method [J]. China Mechanical Engineering, 2002, 13 (6): 464-467.

[4] Ngoi BKA,Teck O C.A tolerancing optimization method for product design[J].The International Journal of Advanced Manufacturing Technology,1997,13(4):290-299.

[5] Chaolin, Huangtian, Wang Yang, et al. Precision design of manufacturing-oriented parallel machine tools [J]. China Mechanical Engineering, 1999, 10 (10): 1114-1118.

[6] Sutherland G H,Roth B.Mechanism design:Accounting for Manufacturing Tolerances and Costs in Function Generating Problems[J].Journal of Engineering for Industry,1975,97(1):60.

[7] Liu Daming, Zheng Jiaoxing. Monte Carlo simulation application in tolerance analysis of poor assembly rate guidance [J].Science and Engineering Technology, 2006,2(4): 67-82.
[8] Ding Wenzheng, Zhou Minghu. Research on precision design of multi-axis machine tools for remanufacturing [J]. Journal of Applied Foundation and Engineering Sciences, 2007 (4): 559-567.

[9] Dufour P, Groppetti R. Computer Aided Accuracy Improvement in Large NCMachine-Tools[M]. Macmillan Education UK, 1981.

[10] Jinqiu, Mo Shuai. Parallel tolerance optimization design based on improved cost tolerance model [J]. Journal of Tianjin University of Science and Technology, 2010, 25 (5): 53-56.