Grinding Method and Error Analysis of Eccentric Shaft Parts

Zhiming Wang1,*, Qiushi Han1, Qiguang Li1, Baoying Peng1, Weihua Li2

1Beijing Information Science & Technology University, Beijing, China
2Beijing Second Machine Bed Factory co., Beijing, China

* Corresponding author e-mail: WZM_Connect@126.com

Abstract. RV reducer and various mechanical transmission parts are widely used in eccentric shaft parts. The demand of precision grinding technology for eccentric shaft parts now. In this paper, the model of X-C linkage relation of eccentric shaft grinding is studied; By inversion method, the contour curve of the wheel envelope is deduced, and the distance from the center of eccentric circle is constant. The simulation software of eccentric shaft grinding is developed, the correctness of the model is proved, the influence of the X-axis feed error, the C-axis feed error and the wheel radius error on the grinding process is analyzed, and the corresponding error calculation model is proposed. The simulation analysis is carried out to provide the basis for the contour error compensation.

1. Introduction

With the advent of intellectualization and digitalization, industrial robots have been gradually applied to various fields of national development. Reducer is an important component that affects the quality and level of industrial robots, and it also marks a country's industrial development level [1]. As the core component of RV reducer, the machining quality and processing efficiency of eccentric shaft directly restrict the development of industrial robots [2]. At present, eccentric shaft grinder processing equipment is relatively backward, processing accuracy can not be guaranteed, low efficiency. The results show that geometrical error and thermal error participate in 60% machining error [3-5]. The testability, modeling and compensation of geometrical errors are the effective methods to improve the machining accuracy [6]. According to the relation of machine motion, the model can reflect the influence of the geometrical error of each axle. Sun D has deduced the expression [7-9] of the relationship between the tracking error and the trajectory error of two linkage axes when machining different trajectories. The research on the errors produced by the servo NC grinder in the grinding process is studied by scholars at home and abroad. The error sources are summarized and summarized [10]. The servo tracking error is the important error source of the eccentric axis contour error, which is caused by the rotation of the grinding wheel frame to follow the main axis, the reciprocating motion of the large stroke and the eccentric shaft workpiece [11]. Another factor affecting the contour error and surface quality is the grinding force and the grinding heat [12-13].

When the tangent point tracking method is used to grind the rotary parts such as eccentric shaft, because of the constant change of the cutting point position and the radius, the calculation of the grinding state of the coordinate and the moving speed of grinding points is more complicated. Aiming at this problem, the paper uses vector method to establish the eccentric axis contour Grinding motion model of the grinding wheel plane rigid body, determines the X-C position relation of the eccentric
shaft workpiece of the linkage wheel, and designs and develops the special software for NC grinding of the eccentric shaft. This paper mainly induces the main influence factors of eccentric axis profile error, establishes mathematical model to solve it, obtains the influence curve of profile error, and provides the basis for the cause of profile error and error compensation.

2. Motion model of wheel-eccentric shaft in eccentric shaft grinding
In the process of machining eccentric shaft, the outer circle of the grinding wheel and the eccentric circle are always tangent, and the center point of the grinding wheel, the centre of eccentric Circle and the tangent point are always in the same line in the grinding process, as shown in Figure 1. Among them, O Point for the workpiece Rotation center, O₂ point for the grinding Wheel center, O₁ point for the eccentric shaft parts Center, r for eccentric circle radius, φ₁ for crank corner, eccentric quantity \( l₁ \), grinding wheel and eccentric shaft contour tangent to A point, there is a closed vector equation, as shown in formula (1).

\[
(r + R) + l₁ = x
\]  

(1)

Figure 1. The kinematic model of the wheel-eccentric axis

The distance between the grinding point and the rotary center of the part is the extreme diameter:

\[
\rho = \sqrt{\left(l₁^2 + r^2 + 2r \cos(\phi₁ + \phi₂)\right)}
\]  

(2)

Position of rotary center of Grinding Wheel center and eccentric shaft parts:

\[
\begin{align*}
x &= l₁ \cos \phi₁ + (r + R) \cos \phi₂ \\
\phi₂ &= \arcsin \left(\frac{-l₁ \sin \phi₁}{r + R}\right)
\end{align*}
\]  

(3)

3. Eccentric shaft grinding model verification
Aiming at the urgency of NC grinding of eccentric shaft, the precision of grinding is improved, the motion model of eccentric shaft grinding and the algorithm above are given. In the Windows
environment, combined with MFC, using C++ language, the development of eccentric shaft grinding CNC software. By the formula (3), the grinding wheel feed curve can be obtained, and the eccentric circle radius is \( r = 26.3 \text{mm} \) in the parameter, eccentricity \( l_1=5.17 \text{mm} \), Wheel radius \( R=250 \text{mm} \). There are other functions such as generating processing G code, setting the following Figure 2:

![Parametric interface and feed curve](image1)

**Figure 2.** Parametric interface and feed curve

In the actual noncircular grinding process, the Non-circular profile envelope is performed by the centripetal linear reciprocating motion of the grinding wheel and the C-axis rotary movement of the eccentric shaft, and the two axes X-C linkage position relationship satisfies the formula (3). In order to facilitate the analysis, the simulation results are shown in Fig. 3 by using the grinding wheel inversion method. It can be seen that the grinding wheel is made of planar rigid body movement around the eccentric shaft, and the eccentric shaft contour is enveloped, and the wheel envelope trajectory coincides with the eccentric axis profile.

![Simulation interface](image2)

**Figure 3.** Simulation interface

4. **Study on profile error of eccentric shaft**

The profile error of the eccentric shaft is the deviation of the normal direction between the instruction position and the actual position at the Contour locus grinding point. The formula (3) shows that the X-C single axis error is not the only influence factor of the profile error. The profile error is closely related to the wheel radius and profile trajectory. This paper mainly studies the error of X and C axis feed error and the radius error of grinding wheel.
4.1. Eccentric Shaft Profile Error

4.1.1 The effect of X-axis feed error on the profile error of eccentric shaft. There are many factors affecting the X-axis feed error, such as the precision of the X-axis horizontal guideway and its positioning accuracy, the vibration or feed delay caused by the grinding force during the X-axis grinding. The X-axis feed error is one of the sources of the profile error of the eccentric shaft grinding, and it is shown from Fig. 4 that the pole diameter error of the eccentric shaft can be approximated as the lift path error of the eccentric shaft.

![Figure 4. Error model of X-axis feed for eccentric shaft grinding](image)

The above figure is known as $\Delta X$ for the X-axis feed error, $\Delta \rho$ for the polar diameter error. The geometrical relation can be used to calculate the profile error $\varepsilon_x$ of the eccentric shaft as shown in formula (4):

$$\varepsilon_x \approx \Delta \rho = \frac{\Delta X}{\cos(\beta)}$$  \hspace{1cm} (4)

By formula (2),(3), The $\beta$ 's calculation formula is as follows:

$$\sin(\beta) = \frac{R \sin(\varphi_1)}{\rho} \Rightarrow \beta = \arcsin \left[ \frac{-l_1 * R \sin(\varphi_1)}{(r + R) * \rho} \right]$$  \hspace{1cm} (5)

4.1.2 The effect of C-axis feed error on the profile error of eccentric shaft. The C-axis feed error is one of the source of the profile error of eccentric shaft, which is mainly caused by the precision of the installation and positioning of the C-axis and the eccentric shaft's pole diameter error caused by the grinding force in the grinding process. As shown in Figure 5:
As above, for the polar error, when the C-axis feed error is $\Delta C$, it can be assumed that $\Delta C = \Delta \phi$, the formula (5) is known, the polar angle $\phi = \beta$, then the eccentric axis profile error $\varepsilon_c$ according to Taylor formula to expand as shown in type (6):

$$
\varepsilon_c = \rho(\phi + \Delta \phi) - \rho(\phi) \approx \rho(\phi) \Delta \phi + \frac{1}{2} \rho(\phi) \Delta \phi^2
$$

(6)

4.1.3 Effect of wheel RADIUS error on profile error of eccentric shaft. In the process of eccentric shaft grinding, the displacement of the X-axis (wheel frame) is the function of the wheel radius, and after the change of the wheel radius, the accurate machining coordinates should be obtained according to the mathematical model. But in fact, it is very difficult to calculate the mathematical model of wheel radius change in real time. At present, the eccentric shaft grinding has been mostly used CBN wheel, grinding wheel durable, small wear, the use of CNC System "tool compensation" function to compensate the grinding wheel radius, can cancel most of the wheel radius error. The wheel radius compensation is essentially the X-axis displacement $\varepsilon_x$ caused by $\Delta R$ increase, but the processing coordinate points are not recalculated, the grinding wheel radius compensation will still cause the eccentric shaft grinding a circle of uneven grinding volume, resulting in a certain degree of lift error. For this analysis, as shown in Fig. 6, the wheel radius error causes the change of grinding point.
Assuming that the normal error of the eccentric shaft profile caused by the wheel radius error is \( \varepsilon_R \), \( \Delta R \) is the grinding wheel radius wear, the grinding point A becomes the \( A' \) point by the grinding wheel radius, the \( \varepsilon_R \) formula is:

\[
\varepsilon_R \approx |AA'| = R - \Delta R \cos(\beta) - \sqrt{(R - \Delta R)^2 - \Delta R^2 \sin^2(\beta)}
\]

(7)

\( \beta \) of the calculated formulas (3), and \( \beta = \varphi_2 \), \( \varepsilon_R \) can be approximated as eccentric axis profile error.

4.2. Simulation Analysis of Profile error

Taking the eccentric shaft of RV reducer as an example, the eccentric shaft radius \( r = 26.3 \) mm, eccentric volume \( l_1 = 5.17 \) mm, Wheel radius \( R = 250 \) mm, Workpiece rotational speed is 6.7r/min, through the cam grinding X, C-axis error analysis [14,15], applied to the eccentric shaft grinding analysis, through the simulation of X, C axis error curve. Assuming that only the X axis produces the error, the x-axis error can be obtained as shown in Fig a. The error curve is fitted by Fig. a, and the effect of the x-axis feed error on the profile error of the eccentric shaft grinding is shown by the formula (2), (3), (4) and (5), as shown in Fig. b:

![Figure 7. X-Axis error condition](image)

Similarly, assuming that only the C-axis produces errors, the C-axis error can be obtained as shown in Figure a. The error curve is fitted by Figure a, and the effect of the C-axis feed error on the grinding profile error of the eccentric shaft is known by the formula (2), (3), (5) and (6), as shown in Figure b:
It is shown from Fig. 7 that the range of the X-axis feed error affects the profile error: The maximum value is 0.001751mm, the minimum value is -0.00144mm; from Fig. 8, the range of error of the C-axis affects the profile error: The maximum value is 0.00180mm, The minimum value is -0.00174mm; Relatively, the C-axis error has a great influence on the profile error.

In the case of ideal grinding of X and C axis, the formula (7) is written into eccentric axis coordinate conversion program, the initial radius of CBN Wheel is 250mm, the lift error of wheel radius wear is calculated, and the result is shown in Fig. 9.

It is shown from the above diagram that when the wheel radius wear is 10mm, 5mm, 1mm, the maximum lift error caused by the grinding wheel radius is 1.82um, 0.89um, and 0.18um. With the increase of the grinding wheel radius, the error of the eccentric shaft lift path is also increasing. At this point, the mathematical model does not need to be recalculated, the eccentric shaft lift error caused by the radius wear of CBN wheel is acceptable after the cutter compensation. When the wear capacity is
greater than 5mm or the ordinary grinding wheel, because of the poor wear resistance, it is necessary to online real-time trimming processing coordinates to meet the processing requirements.

5. Conclusion
In this paper, the eccentric shaft grinding motion model is studied, and the special software of the eccentric shaft NC grinding is developed based on the model algorithm, and the applicability of the X-C position linkage model in the eccentric shaft contour grinding is validated, which is helpful to improve the quality and efficiency of the eccentric shaft grinding process. The error generation mechanism of X-axis, C-axis and grinding wheel radius in grinding process is studied, and the error formation is obviously demonstrated by geometrical modeling and simulation, which provides the basis for the error compensation.

Acknowledgments
This research is funded by National Natural Science Foundation Project of China (Grant No. 51375056 and 51405026), the Beijing Municipal Education Commission Project (Grant No. KM201711232001), and the Beijing Municipal Science and Technology Project (Grant No. Z161100001516002)

References
[1] Wang Qingming, Introduction to Advanced manufacturing technology, M. East China Institute of Chemical Industry Press, 2007.
[2] Lu yan, Research and Analysis of Transmiss Error on RV Reducer in Robot, D. Dalian Jiaotong University. 2013:1-50.
[3] Shen H, Fu J, He Y, Yao X On-line asynchronous compensation methods for static/quasi-static error implemented on CNC machine tools. Int J Mach ToolsManuf, 2012, 60:14-26.
[4] Okafor AC, Ertekin YM, Derivation of machine tool error models and error compensation procedure for there axes vertical machining center using rigid body kinematics. Int J Mach Tools Manuf , 2000, 40(8):1199-1213 .
[5] Jung JH, Choi JP, Lee SJ, Machining accuracy enhancement by compensation for volumetric errors of a machine tool and on machine measurement. J. Mater Process Technol , 2006, 174(1-3):56-66.
[6] Wang Hongjun, Han Qiushi, Li Guanglin, Study on the Intelligent Grinding Paramenter Selecting Model for A CNC Camshft Grinding Machine, J. Manufacturing Technology & Machine Tool, 2003, No.11, pp. 34-36.
[7] Sun D, Tong M C, A synchronization approach for the minimization of contour ingerrors of CNC machine tools, J. IEEE Trans Auto Sci Eng, 2009, 6(4):720-729.
[8] Fan Jinwei, Zhang Lanqing, Wanghong Liang, Yuan Shuai, Machining precision analysis of follower grinder with RV reducer eccentric axis, J. Manufacturing Automation, 2016, 38(9).
[9] Y.Zhou, F. Yu, J. Xu, S. Hong, et al, The cascade type iterative learning cross-coupled contour error control method, Bullentin of Science and Technology, 2011, 27(5):737-739.
[10] Shen Nanyan,Wang Weidong, Li Jing, Cao Yanling, Wang Yu, Modeling and Analysis of Grinding Energy Consumption in Non-circular Grinding Process, J. Journal of Mechanical Engineering, 2017.
[11] Wu Ganghua, He Yongyi, Tian Yingzhong, Research on Motion Model of Constant heq Non-circular Crankshaft Grinding, J. China Mechanical Engineering, 2006, 17(6): 587-589
[12] Kong LB, Cheung CF, Prediction of surface generation in ultra-precision raster milling of option freeform surfaces using an intergrated kinematics error model. Adv Eng Softw(1):2012, 124-136.
[13] X. H. Zhang, Z. H. Deng, W. K. An, H. Cao, A methodology for contour error intelligent precompensation in cam grinding, The International Journal of Advanced Manufacturing Technology, 2013, 64(1-4):165-170.
[14] Peng Baoying, Cai Ligang, Han Qiushi, Yang Qingdong, Li Qiguang, Plane curve parts grinding contour error nonlinear coupling control for X-C direct-drive platform, J. Computer Integrated Manufacturing Systems, 2013-05-17.

[15] Peng Baoying, Li Qiguang, Han Qiushi, Yang Qingdong, Study on adaptive fuzzy Control for grinding profile error of elliptical piston, J. High Technology Letters, 2014.07.016:765-770.