Research on the Machining Error Analysis Method of Globoidal Indexing Cam Profile

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Abstract—**The profile of globoidal indexing cam is spatial undevelopable surface. It needs special CNC machine tool to finish batch production. The machining quality of the profile of globoidal indexing cam could be affected by the movement error of each part of machine tool and the clamped positioning error of workpiece. Firstly, this paper analyses the systematic error of the special machine tool of globoidal cam, derives the error transfer matrix, establishes the mathematical model of the globoidal cam profile which including all machining system errors through multi-body system theory primarily. Secondly, it analyzes the influence caused by each machine tool error and calculates the influence coefficient of machine tool errors. Finally, it simulates the influence of each error on the transmission accuracy of globoidal cam mechanism. This paper lays a theoretical foundation for the distribution of machine errors and the error detection, the error evaluation and the error tracing of globoidal cam profile.**

Index Terms—**globoidal cam, special machine tool, multi-body theory, processing error model**

I. Introduction

The globoidal cam mechanism has been widely used in the ATC of machining center with his many advantages, such as compact structure, high indexing precision, strong bearing capacity, and reliable operation and so on. It is difficult to process globoidal cam profile since it is undevelopable. Globoidal cam profile error can directly reduce the output accuracy, so as to seriously affect scratching and positioning accuracy of manipulator. Therefore, the profile accuracy of the globoidal indexing cam must be strictly guaranteed in the manufacturing process. It is of great practical significance to research the machining error of globoidal cam.

The globoidal indexing cam mechanism was invented by American C. N. Neklutin in 1920s and was first designed, developed, standardized and serialized produced by Ferguson Company founded by him. Because the mechanism is of superior performance and wide application prospect, subsequently the UK, Germany, the former Soviet Union, Hungary, Switzerland, Japan and other countries have also carried out study on the globoidal indexing cam mechanism and the established special manufacturers and research institutions [1]-[3]. A large number of research results are obtained and related technology has become mature. The profile of globoidal indexing cam is spatial undevelopable surface. It is difficult to process. The profile error of globoidal indexing cam will directly reduce the output accuracy of ATC and seriously affect grasping the tool and positioning accuracy of manipulator. Therefore, the profile accuracy of the globoidal indexing cam must be strictly guaranteed during the manufacturing process [4]. The research contents on the error of the globoidal indexing cam include: part error, influence of assembly error on the mechanism output, part error produced by the machining method and error transfer.

There are a number of scholars who have studied the machining error of globoidal cam. Wang [5] from National Chiao Tung University analyzes the influence on output accuracy of globoidal indexing cam mechanism caused by the installation error of three moving directions and three rotating directions in space. H. Y. Cheng [6] from Da-Ye University analyzes the error transfer of globoidal indexing cam mechanism systematically, establishing the error transfer equation, at the same time, he analyzes the sensitivity made by output precision to each error, and establishing the sensitivity equation. Yin Mingfu [7] from Tianjin University of Technology researches on the influence caused by center distance error of globoidal indexing cam machine tool on cam profile error and gives the changing trend of error. Ji Shuting [8], [9] from Beijing University of Technology researches on the influence caused by center distance error of the globoidal indexing cam special machining on the cam profile machining error and draws the influence

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coefficient curve, she reveals the result that the center distance error leads to the error of globoidal indexing cam profile. On the basis of the above research, the influence caused by two rotation shaft errors, three vertical errors and three linear displacement errors of globoidal indexing cam special machining on the machining error of globoidal indexing cam profile have been analyzed [10].

In this paper, based on the working principle of the globoidal cam machine, the mathematical model of the error of globoidal cam profile is established by using the multi-body system theory. Taking the turning error of the globoidal cam as an example, calculating the influence coefficient caused by machine tool error on globoidal cam profile error though Matlab. The variation law of influence coefficient is analyzed, at the same time, the influence of different errors on transmission performance of globoidal cam mechanism is studied [11], [12].

II. Analysis of Cam Special Machine Tool Error

A. Processing Principle of Globoidal Cam

The whole structure of special CNC machine tool for globoidal indexing cam is shown in Fig. 1a, it uses four axes linkage pattern and generating method to process. The four axes are represented by "*A*", "*B*", "*W*" and "*Z*" respectively. Axis *A* and axis *B* are rotating axes, axis *W* and axis *Z* are linear moving axes. While machining globoidal indexing cam, it should not only rotates around its own axis but also swing. The two motions are realized and controlled by the motion of the mutually interactive axis *A* and *B* respectively; the distance between axis *A* and axis *B* is the center distance of globoidal cam indexing mechanism which is adjusted and controlled by axis *W*; axis *Z* realizes the linear feed motion of control cutter along its central axis. The relative motion between workpiece and cutter realized by the linkage of axis *A* and axis *B* is equivalent to the pre-designed relative motion between globoidal indexing cam and driven turntable in the globoidal cam mechanism.

B. Definition of Cam Special Machine Tool Error

It is necessary to consider the many kinds of machine tool errors in the manufacturing process of the globoidal indexing cam. According to the multi-body theory, the motion error model is shown in Fig.1. At this time, there are two branches in the machine tool processing system.

Cutter branch: machine tool body----spindle sliding table axis *Z*----spindle----cutter;

Cam branch: machine tool body----turntable axis *B*----powered support axis *W*----rotary axis *A*----globoidal cam.

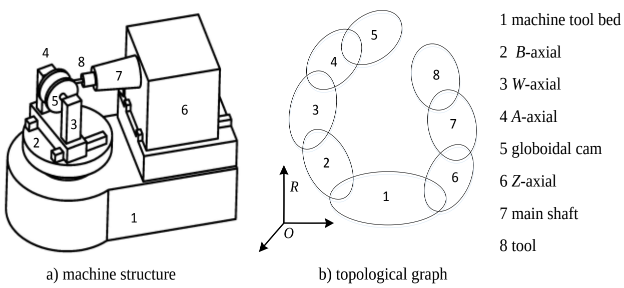


Figure 1. Topology diagram of special machine tool.

There are three linear displacement errors and three angular displacement errors in the spindle, axis *A*, axis *B*, axis *Z* and axis *W*. And it is also necessary to consider the error of cam rotation angle and driven turntable rotation angle and the centre distance error between camshaft and driven shaft, since there is relative motion relation between the cam rotation angle and the driven turntable rotation angle. In order to facilitate understanding, describing the above error decomposition diagram according to the machine tool structure in Fig.1, as shown in Fig. 2. The error definition of globoidal cam machine too and symbolic representation are shown in Table I.

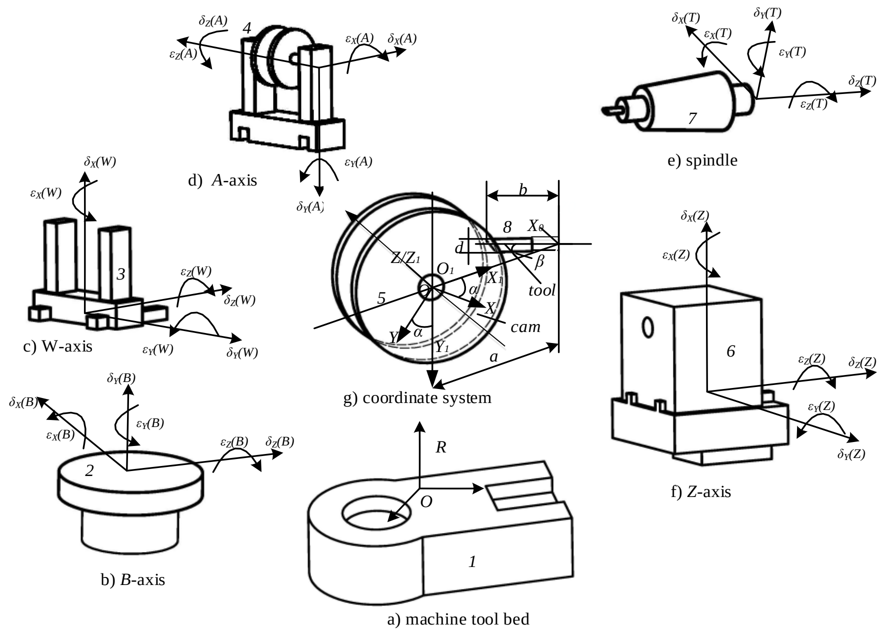


Figure 2. Error definition of special machine tool.

Fig. 2 defines the error coordinates of moving parts of the globoidal indexing cam special machine tool. Fig.2a is the machine tool bed, Fig.2b is axis *B*, Fig.2c is axis *W*, Fig.2d is axis *A*, Fig.2e is the spindle, Fig. 2f is axis *Z*.

C. Feature Transformation Matrix

The feature transformation matrix of multi-body system is represented by homogeneous coordinate. Homogeneous coordinate transformation includes six transformation modes: linear displacement along three coordinate axes and angular displacement around three coordinate axes. According to the theory of homogeneous coordinate transformation, we can get each feature transformation matrix between each moving body and its adjacent low-sequence body. Therefore, the transformation matrix of error coordinate system of spindle error of machine tool, the axis *B*, rotating axis *A*, power support axis *W* and the spindle sliding table axis *Z* can be obtained. The transformation matrix includes linear displacement matrix and angular Displacement matrix.

Taking the transformation matrix of the error coordinate system about machine tool spindle as an example, the linear displacement transformation matrix includes: the t_{TX} of *X* axis direction, the t_{TY} of *Y* axis direction, the t_{TZ} of axis *Z* direction which are the error coordinate system along machine tool spindle. The transformation matrix of angular displacement includes: error coordinate system around machine tool spindle---- the r_{RX} which rotates around *X* axis, the r_{RY} which rotates around the *Y* axis, the r_{RZ} which rotates the axis *Z*.

$$t_{TX}=\begin{bmatrix}1&0&0&\delta_X(T)\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\tag{1}$$

$$t_{TY}=\begin{bmatrix}1&0&0&0\\0&1&0&\delta_Y(T)\\0&0&1&0\\0&0&0&1\end{bmatrix}\tag{2}$$

$$t_{TZ}=\begin{bmatrix}1&0&0&0\\0&1&0&0\\0&0&1&\delta_Z(T)\\0&0&0&1\end{bmatrix}\tag{3}$$

$$r_{RX}=\begin{bmatrix}1&0&0&0\\0&\cos(\varepsilon_X(T))&\sin(\varepsilon_X(T))&0\\0&-\sin(\varepsilon_X(T))&\cos(\varepsilon_X(T))&0\\0&0&0&1\end{bmatrix}\tag{4}$$

$$r_{RY}=\begin{bmatrix}\cos(\varepsilon_Y(T))&0&-\sin(\varepsilon_Y(T))&0\\0&1&0&0\\\sin(\varepsilon_Y(T))&0&\cos(\varepsilon_Y(T))&0\\0&0&0&1\end{bmatrix}\tag{5}$$

$$r_{RZ}=\begin{bmatrix}\cos(\varepsilon_Z(T))&\sin(\varepsilon_Z(T))&0&0\\-\sin(\varepsilon_Z(T))&\cos(\varepsilon_Z(T))&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\tag{6}$$

Similarly, the linear displacement and angular displacement matrix of error coordinate system of turntable axis *B*, the rotating axis *A*, the power support axis *W* and spindle slide table of *Z* can be obtained respectively. The representation method of the transformation matrix of each axis about the machine tool are shown in Table II.

TABLE I. ERRORS OF THE SPECIAL MACHINE TOOL

Error Type	Linear offset error			Rotational error		
Error Direction	*X*	*Y*	*Z*	*X*	*Y*	*Z*
Spindle	$\delta_X(T)$	$\delta_Y(T)$	$\delta_Z(T)$	$\varepsilon_X(T)$	$\varepsilon_Y(T)$	$\varepsilon_Z(T)$
Z-axis	$\delta_X(Z)$	$\delta_Y(Z)$	$\delta_Z(Z)$	$\varepsilon_X(Z)$	$\varepsilon_Y(Z)$	$\varepsilon_Z(Z)$
B-axis	$\delta_X(B)$	$\delta_Y(B)$	$\delta_Z(B)$	$\varepsilon_X(B)$	$\varepsilon_Y(B)$	$\varepsilon_Z(B)$
W-axis	$\delta_X(W)$	$\delta_Y(W)$	$\delta_Z(W)$	$\varepsilon_X(W)$	$\varepsilon_Y(W)$	$\varepsilon_Z(W)$
A-axis	$\delta_X(A)$	$\delta_Y(A)$	$\delta_Z(A)$	$\varepsilon_X(A)$	$\varepsilon_Y(A)$	$\varepsilon_Z(A)$
Cam Angle	--	--	--	--	--	$\Delta\alpha$
Turntable Angle	--	--	--	--	--	$\Delta\beta$
Center Distance	Δa	--	--	--	--	--
Turntable	$\delta_X(S)$	$\delta_Y(S)$	$\delta_Z(S)$	$\varepsilon_X(S)$	$\varepsilon_Y(S)$	$\varepsilon_Z(S)$

TABLE II. REPRESENTATION METHOD OF TRANSFORMATION MATRIX

Coordinate System	*Linear Displacement*			*Angular Displacement*		
	X	*Y*	*Z*	*X*	*Y*	*Z*
Spindle	t_{TX}	t_{TY}	t_{TZ}	r_{RX}	r_{RY}	r_{RZ}
B-axis	t_{BX}	t_{BY}	t_{BZ}	r_{BX}	r_{BY}	r_{BZ}
A-axis	t_{AX}	t_{AY}	t_{AZ}	r_{AX}	r_{AY}	r_{AZ}
W-axis	t_{WX}	t_{WY}	t_{WZ}	r_{WX}	r_{WY}	r_{WZ}
Z- axis	t_{ZX}	t_{ZY}	t_{ZZ}	r_{ZX}	r_{ZY}	r_{ZZ}
Cam Angle	--	--	--	--	--	r_α
Turntable Angle	--	--	--	--	--	r_β
Center Distance	--	--	t_a	--	--	--

III. ESTABLISHMENT OF CAM PROFILE EQUATION

When deriving the globoidal indexing cam profile equation, there are three rectangular coordinate systems are established, as shown in Fig.2. The coordinate system $O_0X_0Y_0Z_0$ is a fixed coordinate system, its origin O_0 is the intersection point between the center axis of cutter and the swinging centerline of the workpiece, that is, the intersection point of the center axis of the axis *Z* and the axis *B*. The O_0Z_0 axis overlaps with the centreline of cutter, that is, overlapping with axis *Z*. The O_0Y_0 axis overlaps with the swinging centerline of the workpiece, that is, overlapping with the centerline when axis *B* move. The coordinate system $O_1X_1Y_1Z_1$oscillates around the axis *B* and theO_1Z_1 axis overlaps with the workpiece rotation centreline, that is, it overlaps with the centerline when axis *A* move; The O_1X_1 axis overlaps with the line O_1O_0, that is, parallel with the axis *W*. And the coordinate system is fixed with workpiece. Making the coordinate system$O_1X_1Y_1Z_1$ rotates around the O_1Z_1 axis, the rotation angle is equal to the angular Displacement of axis A movement, then we can get the coordinate system $OXYZ$. The point P on the centerline of cutter is a random point on the theoretical profile after processing. The theoretical profile of globoidal indexing cam is generated by using point P and through the generating method. In Fig. 2, b is the distance between the point P and the point O_0, d is the diameter of cutter, a is the distance between the axis A rotation center line and the axis B swing centerline of machine tool, that is the distance between cam rotation center axis line and the cam swing center axis line, which is called center distance. The relation between αandβ is determined by the motion law of a pre-designed globoidal indexing cam mechanism, which is a known condition.

According to the coordinate system established in Fig.2 and the feature transformation matrix based on multi-body theory, the position vector $p_0$of point P in coordinate system $O_0X_0Y_0Z_0$is as follows:

$$p_0 = \begin{pmatrix} x_0 \\ y_0 \\ z_0 \end{pmatrix} = (t_{BX} t_{BY} t_{BZ} r_{BX} r_{BY} r_{BZ}) \times (t_{ZX} t_{ZY} t_{ZZ} r_{ZX} r_{ZY} r_{ZZ})(t_{TX} t_{TY} t_{TZ} r_{TX} r_{TY} r_{TZ}) t_b \tag{7}$$

The position vector p_1 of point P in coordinate system$O_1X_1Y_1Z_1$is as follows:

$$p_1 = \begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} = (t_{WX} t_{WY} t_{WZ} r_{WX} r_{WY} r_{WZ}) r_\beta p_0 + t_a \tag{8}$$

The position vector p of point P in the coordinate system $OXYZ$ is as follows:

$$p = \begin{pmatrix} x \\ y \\ z \end{pmatrix} = t_\alpha p_1 \tag{9}$$

The unit normal vector of theoretical profile after machining is as follows:

$$n = \frac{\dfrac{\partial p}{\partial b} \times \dfrac{\partial p}{\partial \alpha}}{\left| \dfrac{\partial p}{\partial b} \times \dfrac{\partial p}{\partial \alpha} \right|} \tag{10}$$

The actual profiles on both sides of the processing are represented by p_l and p_r respectively, and the solution is as follows:

$$p_l = p - \frac{d}{2} n \tag{11}$$

$$p_r = p + \frac{d}{2} n \tag{12}$$

Adding the equation (9), (10) to the equation (11), (12), the error model of globoidal indexing cam profile could be obtained.

Setting all the error value in Table 1 as 0, then the theoretical profile equation of globoidal indexing cam could be obtained.

IV. Influence of Machine Tool Error on Profile

A. Establishment of Processing Error Model

Combine with machined globoidal cam profile derived in Section 2, the final profile deviation $f(X)$ of the machined globoidal cam could be described as the projection of the deviation vector of the cam surface on the direction of the surface normal vector n_d:

$$f(X) = (p - p_d) \cdot n_d \tag{13}$$

where $\partial f / \partial x_i$ can be known as influence coefficient. Where p and p_d represent he machined globoidal cam profile and the theoretical globoidal cam profile respectively. Vector X is deviation vector of machine tool, and $X=(x_1, x_2, \ldots, x_n)$, n shows the number of machine tool errors. Thus, while the deviation vector $X=0$, p is equal to p_d.

In order to predict deviation of final product, the first two terms of Taylor series of $f(X)$ in equation (12) at $X_0=0$ can be written as:

$$f(X) \approx f(X_0) + \sum_{i=1}^{n} \left(\frac{\partial f}{\partial x_i} \right) x_i, X = (x_1, x_2, \cdots, x_n) \tag{14}$$

B. Analysis of Globoidal Cam Profile Error

Analyzing the machining error of the globoidal cam special machine tool based on the theory of multi-body system, it can be seen that there are many factors affecting the error of the globoidal cam profile, next, taking the globoidal cam rotation angle error $\Delta\alpha$as an example to carry on the detailed analysis and research.

In order to study the influence of globoidal cam rotation angle error on the globoidal cam profile error, first, the influence coefficient of machine tool error on the globoidal cam profile error should be calculated, through the influence coefficient to research on the effect caused by angle error on the globoidal cam profile error. According to equation (14), the expression of the influence coefficient of cam angle error $\Delta\alpha$ is shown as follows:

$$\frac{\partial f}{\partial x_1} = \frac{\partial f}{\partial(\Delta\alpha)} = \frac{\partial[(p - p_N) \bullet n_d]}{\partial(\Delta\alpha)} \tag{15}$$

Because of $p_d \perp n_d$, and adding the (9) and (10) to (16), the (16) can be simplified as follows:

$$\frac{\partial f}{\partial x_1} = \frac{\partial f}{\partial(\Delta\alpha)} = \frac{\partial[(p \pm \frac{d}{2} n) \bullet n_d]}{\partial(\Delta\alpha)} \tag{16}$$

Because of the small machine tool error, $n \bullet n_d$=1. The (17) could be simplified as follows:

$$\frac{\partial f}{\partial x_1} = \frac{\partial f}{\partial(\Delta\alpha)} = \frac{\partial(p)}{\partial(\Delta\alpha)} \bullet n_d \tag{17}$$

The final expression of the influence coefficient of cam rotation error $\Delta\alpha$ is shown as follows:

$$\frac{\partial f}{\partial x_1}=\frac{\partial f}{\partial(\Delta\alpha)}=\frac{\partial(p)}{\partial(\Delta\alpha)}\bullet n_d=\begin{bmatrix}-(-b\cos\beta+a)\sin\alpha\\-(-b\cos\beta+a)\cos\alpha\\0\end{bmatrix}\bullet n_d \tag{18}$$

Adding the dimension data, motion rules and other parameters of TC40 globoidal cam and n_d to (18), and$\Delta\alpha$ is calculated by Matlab. The influence coefficient curve of $\Delta\alpha$ is shown in Fig. 3. In Fig. 3, the surface marked by "1", "2", “3” and “4” are used to express the changing condition of globoidal cam profile error generated from 4 times of cutter path while processing the globoidal cam.

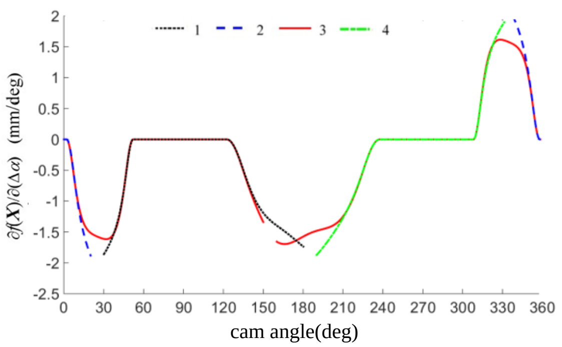


Figure 3. Influence coefficient curve of cam rotation error Δα.

In order to clearly show the influence caused by $\Delta\alpha$, and then further study on the influence of motion rules caused by $\Delta\alpha$ to actual globoidal indexing cam mechanism, taking the $\Delta\alpha=0.01°$ degrees and other errors are 0 to undertake the research. In the condition of $\Delta\alpha=0.01°$ and other errors are 0, the simulating globoidal cam profile error is calculated through Matlab, the results are shown in Fig. 4. Fig. 4a is the changing situation caused by driven parts angular displacement error of left actual profile following with cam rotation angle and groove depth. Fig. 4b is the changing situation caused by driven parts angular displacement error of right actual profile following cam rotation angle and groove depth.

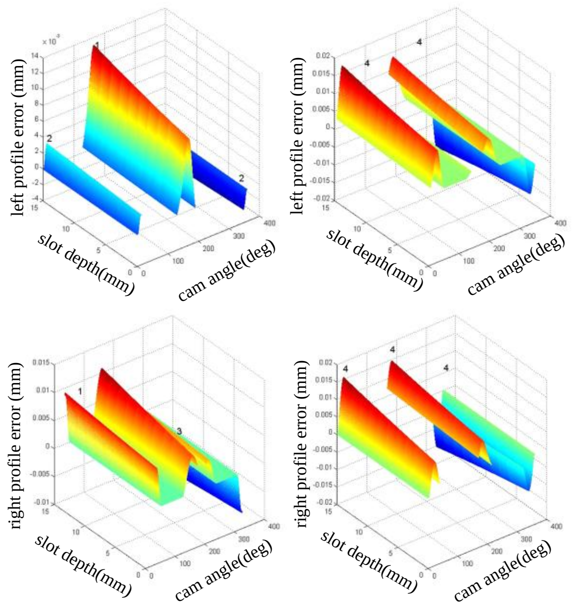


Figure 4. Profile error at Δα=0.01 °.

In order to make the analysis more visual, the changing situation of profile error at the maximum groove depth when Δα=0.01° is calculated. The error variation curve is shown in Fig. 5.

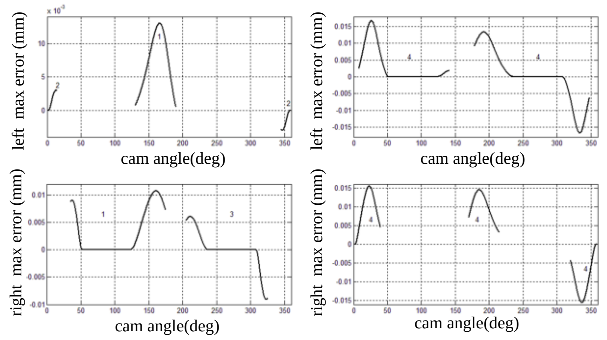
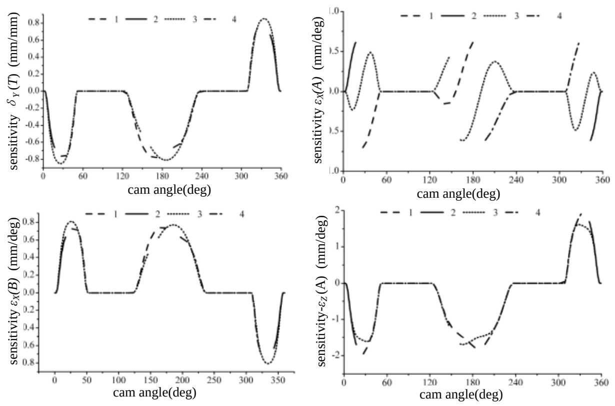
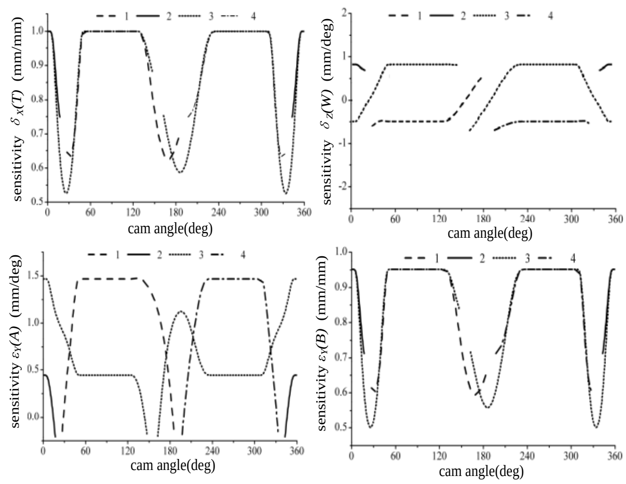


Figure 5. Profile error variation curve of maximum groove depth at Δα=0.01 °.

Through the comparative analysis of Fig. 3, Fig. 4 and Fig. 5, the influence caused by $\Delta\alpha$is shown as follows: 1) in the rest section, the error $\Delta\alpha$ has no effect on the globoidal cam profile; 2) in the indexing section, with the increase of the rotation angle of driven plate in cam mechanism, and surface the error of globoidal cam profile brought by $\Delta\alpha$ also becomes larger, the maximum value can reach to 2mm/deg, and the error gradually increasing along the direction of cam groove depth.



a) Curve in the rest section as the influence coefficient is zero



b) Curve in the rest section as the influence coefficient is not zero

Figure 6. Influence coefficient of different errors of machine tool.

The influence coefficient caused by various errors can be obtained by the above method, and simulating by Matlab to get influence coefficient curve. Fig. 6 are the influence coefficient curves of error 1, error 2 and error 3. Through comparing the influence coefficient curve of each error, the influence curve could be divided into two categories: one is in the rest section, the coefficient is zero, as shown in Fig.6 a); the other shows the influence coefficient is not zero, as shown in Fig. 6 b).

C. Application of Globoidal Cam Profile Error Model

The quality of the globoidal cam profile is guaranteed by the machining accuracy of the machine tool, and increasing the accuracy will increase the manufacturing cost. The various errors of the machine tool have a certain influence on the machining error of globoidal cam profile. According to this paper, the error transfer equation and the influence coefficient equation can be derived, at the same time, the optimization model can be considered both in cost and accuracy, so as to reasonably allocate the tolerance in each link and each part. Further reduce the manufacturing cost on the basis of guaranteeing machining accuracy.

After finishing the machining of the globoidal cam, it is necessary to measure the quality of the profile, as for the complex surface, the coordinate measuring machine is usually used to do the precise measurement, so as to decide whether the globoidal cam can meet the demands of assemble. The theoretical model during globoidal cam profile error measurement and evaluation can be established according to the error modeling process proposed in this paper.

In order to guarantee the machining quality of globoidal cam profile, it is necessary to improve the accuracy maintenance of machine tool. According to the test result of workpiece profile error, through the method of error separation and tracing to find out the specific factors that affect the profile error can realize the adjustment of machine tool error, the machining process correction and the error compensation in the machining process, so as to improve the machining quality. The error tracing of globoidal cam machine tool can be divided into groups according to the analysis result of Fig.8: that is, first, through the measurement data in rest section to trace the machining error factor whose error coefficient is not zero, then, tracing other machining error factor through indexing sections, which could improve the speed of data processing and the accuracy.

V. Conclusion

This paper researches on the influence caused by error of globoidal cam special machine tool on the error of globoidal cam profile, the machining error of special machine tool and coordinate transformation matrix is analyzed by using multi-body system theory, at the same time, the error model of the globoidal indexing cam profile is established, which lays certain foundation for the integration of design, processing and measurement to globoidal cam mechanism. The main conclusions are as follows:

1) According to the structure of globoidal cam special machine tool, establishing the machine tool error transformation matrix based on multi-body system theory, and the mathematical model of globoidal cam profile error is established according to the generating machining theory of globoidal cam.

2) Through analyzing the mathematical model of globoidal cam profile, researching on the influence of machine tool error on globoidal cam profile error, so as to establish the mathematical model of the influence coefficient of machine tool error, and through the concrete examples and analysis, the influence degree of machine tool error on globoidal cam profile under different cutter track could be represented clearly.

3) Through PROE modeling and Matlab simulation, paying more attention on researching the variation law of globoidal cam profile error caused by $\Delta\alpha$, and analyzing the influence of globoidal cam profile error on transmission accuracy.

The establishment of mathematical model of globoidal cam profile machining error lays the theoretical basis for precision design and error distribution of special machine tool for globoidal cam profile, the quality detection and error evaluation of globoidal cam profile, and the tracing for globoidal cam machining error.

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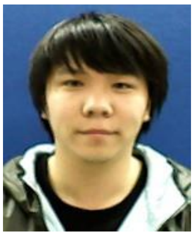

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