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Accuracy test for cam profile based on accuracy theory of globoidal cam mechanism

Wei Sun[1], Zikai Wang[1], Juan Wang[1], Chengyu Yuan[1]

Abstract. Parameterization of globoidal indexing cam has been realized in this paper with computer aided design; simplification for design process of globoidal indexing cam has been made with adoption of regular curves, curved surface and other commands in UG. Several error factors affecting kinematic accuracy of globoidal cam mechanism have been analyzed and mathematical model of meshing of globoidal cam mechanism with error has been set up. Differential precision analysis method has been adopted to get the expression of influence coefficient of each error factor on kinematic accuracy of globoidal cam mechanism; the change rule of each influence coefficient of kinematic accuracy with the change of globoidal cam angle has been analyzed through examples. The analysis has shown that the influence of each error factor on kinematic accuracy of globoidal cam mechanism is the same; roller radius error has the greatest influence on its kinematic accuracy; the shaft angle error has the smallest influence on its kinematic accuracy; the influence of meshing point position on its kinematic accuracy is the most unstable; each influence coefficient is related to basic structure size factor of globoidal cam mechanism.

Key words. Cam, Globoidal, Parameter, Accuracy, Error.

1. Introduction

In the processing of globoidal indexing cam, center distance error, tool radius error, tool rotation error and others during processing will cause profile error of cam and then cause meshing clearance or interference in assembly process, which affects dynamic performance under high speed motion and decreases indexing and positioning accuracy of driven disk. Therefore, studying manufacturing error of globoidal cam or influence factor of processing accuracy and exploring effective measurement method is the key of ensuring the quality of globoidal indexing cam mechanism.

[1]Mechanical and electrical engineering college of Hainan university, Hainan, Haikou, China

Someone has designed transmission accuracy and motion parameter detection system for globoidal indexing cam mechanism. Someone has adopted vector method to analyze the original processing error of globoidal cam profile as well as its influence on follower motion law of globoidal indexing cam mechanism. Three-coordinate measuring machine is an effective method of accurate measurement of complex surface and is also the main tool for realizing accurate measurement of globoidal cam. Someone has made exploration for accuracy measurement of globoidal cam with adoption of three-coordinate measuring machine. At present, there are globoidal cam series of products in China. It is urgent to set up complete and reasonable accuracy index system. Someone has proposed the assumption of constructing accuracy index system of globoidal indexing cam mechanism and proposed the items that should be tested for cam contour surface.

2. Globoidal indexing cam mechanism

Globoidal indexing cam mechanism is used for the intermittent indexing stepping drive between two vertical interlaced shafts. Active cam is circular arc revolving body and the cam contour is made into convex ridge shape or groove shape, which is similar to globoidal worm with variable helix angle. Install two rollers on the outer circle of driven disk, with axis distributes evenly along turntable radial. Turntable equals to worm gear and roller equals to the tooth of worm gear. Therefore, globoidal cam has single head, multiple heads, left rotating and right rotating; the relationship between cam and rotating direction of turntable can be determined by method similar to worm & worm gears. In practical application, left rotating adopts most and the one bigger than three heads is seldom used. Globoidal indexing cam mechanism can be divided into convex ridge and groove type based on its differences in location segment form, as shown in figures 2-1. Convex ridge type cam positioning section is ridge. Two rollers of indexing plate are installed on two sides of convex ridge. The positioning section of groove type cam is groove; one roller on indexing plate is in positioning groove. No matter for which cam, its convex ridge has left and right two sides. According to different rotation directions, one side is stress side, which promotes the turning of indexing plate; the other side is geometric positioning side and there is some gap between local area and roller. In this way, it can realize that continuous rotation of cam drives intermittent indexing motion of indexing plate, and then the transmission between two vertical interlaced shafts can be transferred.

3. Basic parameters of globoidal indexing cam mechanism

3.1. Major kinematic parameters of globoidal indexing cam mechanism

Major kinematic parameters of globoidal indexing cam mechanism are as following:

(1) Number of cam indexing contour H: for the roller number dialed by cam at

each graduation, it adopts the concept of worm thread head number. The commonly used ones include single head H=1, double heads H=2 and multiple heads H $\geq$ 3; the multiple heads are seldom used.

(2) Rotation direction of cam indexing contour and coefficient of rotation direction p: left rotating (L), $p = +1$; right rotating (R), $p = -1$; it usually adopts left rotating cam.

(3) Turntable indexing number I: the rotation and stop times of turntable in one-circle turning process is determined by requirements of mechanical production process. The commonly used ones include 3, 4, 5, 6, 8, 10, 12 and 16.

(4) Roller number of turntable Z: A=HI

Usually Z is even number and the commonly used ones include 6, 8, 10, 12 and 16.

(5) Angular velocity of cam

$$\omega_1 = 2\pi n/60\,. \tag{1}$$

n is cam speed requested by working conditions in design.

(6) Cam indexing period angle (indexing angle) θ_h and resting period angle θ_f: the rotated angle of cam within moving time of moving parts is cam indexing period angle and the value is usually $2\pi/3 - 4\pi/3$. Under the demand of meeting dynamic and resting ratio, it should select bigger value. Resting period angle:

$$\theta_h = 2\pi - \theta_f\,. \tag{2}$$

(7) Transposition angle during turntable indexing period θ_d: one motion cycle with one rotation and one stop is an indexing; the angle of one indexing rotated from moving parts is transposition angle.

$$\theta_d = 2\pi/I\,. \tag{3}$$

(8) Angular displacement of turntable ϕ_i:

$$\phi_i = S\theta_d\,. \tag{4}$$

S is dimensionless displacement of selected law of motion and V is dimensionless velocity of selected law of motion.

(10) Dynamic and resting ratio k:

$$k = \theta_h/\theta_f\,. \tag{5}$$

3.2. Major geometric parameters of globoidal indexing cam mechanism

As shown in figure 1, major geometric parameters of globoidal indexing cam mechanism include:

(1) Roller size, roller width B and roller diameter Ro can be determined by contact stiffness. It is usually designed with analogy method and selects standard

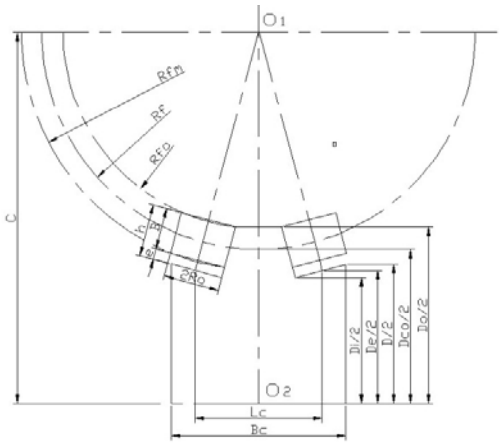

Fig. 1. Major geometric parameters of globoidal indexing cam mechanism

parts.

(2) Distance e between roller and bottom of cam groove along roller height direction. Generally it takes:

$$e = (0.2 \sim 0.3)B; \text{and } e = 5 \sim 10\text{mm}\,. \tag{6}$$

(3) Length of cam positioning torus side h:

$$h = B + e\,. \tag{7}$$

(4) Driven disk size, R_f is radius of driven disk and it is the radium from rotating center of driven disk to central axis of roller width. It is the main size of driven disk and can be estimated with following formula:

$$R_f = \frac{R_o}{\sin\frac{\theta_d}{4}} \pm (1\,\mathrm{dim}\,5)\,. \tag{8}$$

(5) Radius of driven disk circle R_{fo}:

$$R_{fo} = \sqrt{(R_f - \frac{1}{2}B)^2 + R_o{}^2} \tag{9}$$

(6) Maximum outer radius of driven disk R_{fm}:

$$R_{fo} = \sqrt{(R_f - \frac{1}{2}B)^2 + R_o{}^2} \tag{10}$$

(7) Radius of cam pitch circle D_{co}: under the premise of ensuring contact stress and pressure angle smaller than allowable value, the cam size should not be too big, so that the mechanism can be compacting as much as possible. Radius of cam pitch

circle D_{co} can be estimated with following formula:

$$D_{co} = \frac{HV_m}{\theta_h \tan[\varphi]} \,. \tag{11}$$

(8) Central distance C:

$$C = D_{co}/2 + R_f \,. \tag{12}$$

(9) Actual width of cam B_c:

$$B_c \approx 2\left(R_f \sin\frac{\tau_h}{2} + \frac{Ro}{cos\frac{\tau_h}{2}}\right) . \tag{13}$$

(10) Theoretical width of cam L_e:

$$L_e = 2(R_f + B/2 + e)\sin(\theta_d/2) \,. \tag{14}$$

3.3. Law of motion of globoidal indexing cam mechanism

The law of motion of globoidal indexing cam mechanism refers to the output law of motion of driven disk, which reflects the function between angular displacement of driven disk and cam angular displacement θ or cam operation time t is to ensure periodicity and realize stepping accurately. The law of motion curve requested by globoidal indexing cam mechanism must be with stable motion, small impact load, long life and accurate indexing; therefore, it usually adopts sinusoidal acceleration, modified equal velocity, modified sinusoidal acceleration, improved trapezoidal acceleration and other laws of motion. Figure 2 is the law of motion curve of modified sinusoidal acceleration.

3.4. Equation of working profile of globoidal cam

The curved surface between globoidal cam and actual working surface of indexing roller is working profile. When solve the equation of working surface of globoidal cam, select suitable coordinate system, which can not only simplify calculation process, but also affect the form of formula. In this paper, we select Cartesian coordinate. The coordinate system shown in figure 3 calculates coordinate equation of working surface of goboidal cam with principle of conjugate surfaces. In the figure, four sets of rectangular coordinate system set up by us are as following: fixed coordinate system connected with frame $O_o x_o y_o z_o$; auxiliary coordinate system connected with frame $O'_o x'_o y'_o z'_o$. When select Z'_O direction, ω_1 should be in counter-clockwise direction when look at $Z'{}_O$ arrow; dynamic coordinate system connected with cam $1 O_1 x_1 y_1 z_1$; dynamic coordinate system $O_2 x_2 y_2 z_2$ connected with indexing plate 2.

The coordinate equation of indexing plate roller cylindrical surface in dynamic

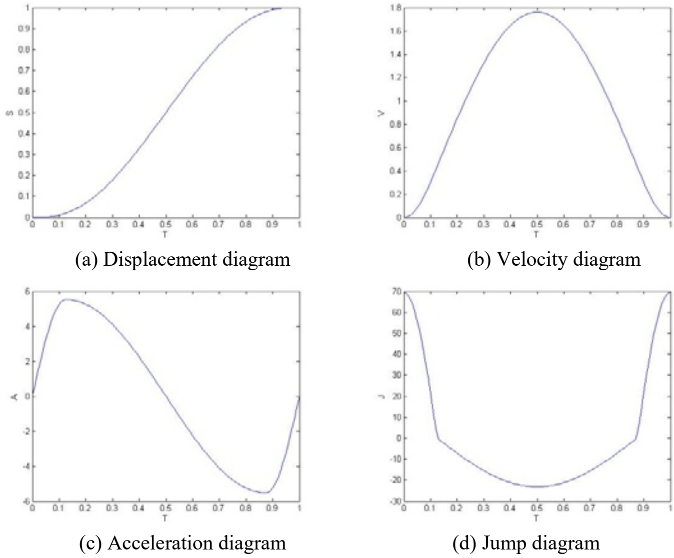

Fig. 2. Law of motion curve of modified sinusoidal acceleration

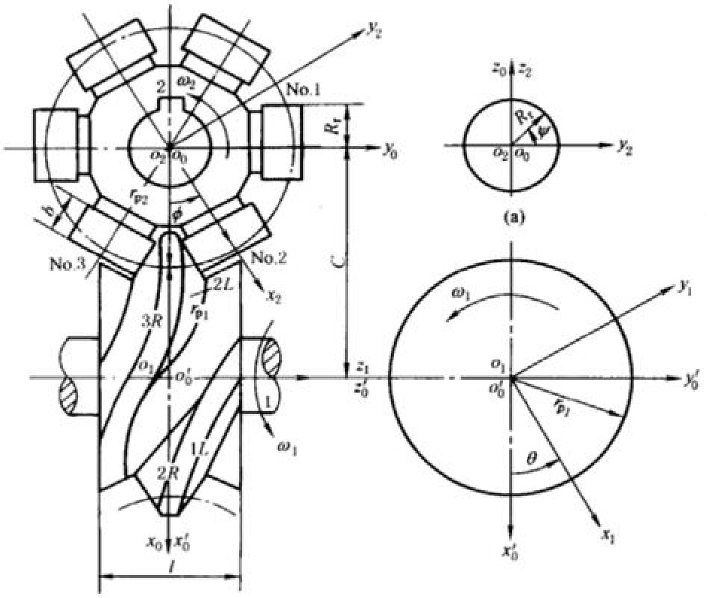

Fig. 3. Coordinate system of globoidal indexing cam (look at x_2 arrow, roller is perpendicular to the section of x_2 axis at r place; look at arrow z_1, it passes cam center O_1 and is perpendicular to z_1 and is the cam section of r_{p1})

coordinate system $O_2x_2y_2z_2$ is:

$$\begin{cases} x_2 = r\,, \\ y_2 = R_r \cos\Psi\,, \\ z_2 = R_r \sin\Psi\,. \end{cases} \tag{15}$$

In the formula, r and Ψ are equation parameters of roller cylindrical surface:
Conjugate contact equation of globoidal cam and roller is $\tan\Psi = \frac{pr}{C - r\cos\varphi}\left(\frac{\omega_2}{\omega_1}\right)$
In the formula, φ is the position angle of roller.

The coordinate equation of cam working profile in coordinate system $O_1x_1y_1z_1$ is:

$$\begin{cases} x_1 = r\cos\theta\cos\phi - R_r\cos\psi\cos\theta + R_r\sin\psi\sin\theta - C\cos\theta \\ y_1 = -r\sin\theta\cos\phi + R_r\cos\psi\sin\theta - R_r\sin\psi\cos\theta + C\sin\theta \\ z_1 = pr\sin\phi + R_r\cos\psi cos\phi \end{cases} \tag{16}$$

In the formula, θ is globoidal cam angle, p is rotation coefficient of cam, when it is left rotating, $p = +l$; when it is right rotating, $p = -1$.

3.5. Establishment of theoretical profile equation

In the mesh drive of globoidal cam and indexing roller, the trajectory surface of roller centerline scanned in space is theoretical profile. When solve the equation of theoretical profile, we adopt the advantages of homogeneous transformation method. The advantage of homogeneous transformation lies in connecting motion, transformation, mapping with matrix motion. It describes the translation and rotation of coordinate system completely through a matrix. It has been applied extensively in dynamics of spatial mechanisms, robot control algorithm, computer graphics, visual information processing and other fields. Homogeneous transformation matrix is as shown in following formula. T_{ij} describes the position and direction of coordinate system (i) to (j).

$$T_{ij} = \begin{bmatrix} B_{33} & & & P \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

The coordinate equation of indexing roller center line in coordinate system $O_ox_oy_oz_o$ is:

$$\begin{cases} x_o = r\cos\phi \\ y_o = r\sin\phi \\ z_o = 0 \end{cases} \tag{17}$$

Its vector form can be expressed as $R^{(0)} = (r\cos\varphi, r\sin\varphi,\ 0, 1)$

Set one point D at center line of indexing plate, vector radius in coordinate system $O_1x_1y_1z_1$ is $R^{(1)}$, vector radius in coordinate system $O_ox_oy_oz_o$is $R^{(0)}$; the change matrix from coordinate system $O_o'x_o'y_o'z_o'$ to $O_1x_1y_1z_1$ is T_{10}; the change matrix from coordinate system $O_ox_oy_oz_o$ to $O_o'x_o'y_o'z_o'$ is T_{00}, it can be learnt that:

$$T_{10} = \begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, T_{00} = \begin{bmatrix} 1 & 0 & 0 & -C \\ 0 & 1 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}.$$

After a series of matrix changes, the coordinate equation of roller center line at

r in coordinate system $O_1x_1y_1z_1$ is:

$$R^{(1)} = T_{10}T_{00}R^{(0)} = \begin{bmatrix} \cos\theta & \sin\theta & 0 & 0 \\ -\sin\theta & \cos\theta & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & -C \\ 0 & 1 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} r\cos\varphi \\ r\sin\varphi \\ 0 \\ 1 \end{bmatrix}$$
$$= \begin{bmatrix} r\cos\phi\cos\theta - C\cos\theta \\ -r\sin\theta\sin\phi + C\sin\theta \\ r\sin\phi \\ 1 \end{bmatrix}.$$

After summarizing matrix equation with coordinate change, it can be learnt that the theoretical profile equation of globoidal cam is:

$$\begin{cases} x_1 = r\cos\phi\cos\theta - C\cos\theta \\ y_1 = -r\sin\theta\sin\phi + C\sin\theta \\ z_1 = pr\sin\phi \end{cases} \tag{18}$$

4. Serial design of cam modeling

Draw the trajectory curves of two roller ends as shown in figures 3-8 with adoption of regular curve command. It is tool path of equal diameter tool, which is the trajectory of central point of indexing roller adding safety clearance as well as the trajectory of another point on center line of roller.

Fig. 4

Fig. 5

(2) Set up rules surface as shown in figures 4-5 by taking two trajectories as guiding lines.

(3) Thicken ruled surface solid, which is the cutting solid of tool in the space, as shown in figures 6-7

(4) Adopt attained profile solid and rough to make Boolean operation (dif-ference) and finally revise to attain cam solid as shown in figures 8-11.

(5) Adopt the same method to make modeling for cams with dynamic resting ratios 1/3, 1/5, 2/3, 3/5 and other four cams with different dynamic resting rati-os.

Figures 8-11 have been attained.

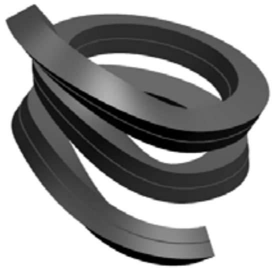

Fig. 6

Fig. 7

Fig. 8. Dynamic resting ratio 1/3

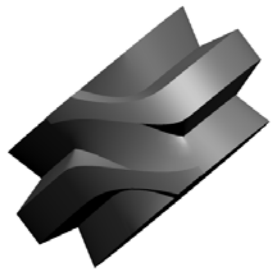

Fig. 9. Dynamic resting ratio 1/5

Fig. 10. Dynamic resting ratio 2/3

Fig. 11. Dynamic resting ratio 3/5

The machine tool structure determines is processing range. Not all the five-axis CNC machine tools are suitable for processing globoidal cam. Globoidal cam can be regarded as six-sides processing to some extent. It is not enough for the machine tool to implement five-side processing and it needs two clamping to finish the cutting completely, which decreases processing accuracy and can't realize expected target. It also restricts the universality of using machine tool and causes limitations for this method.

Through comparative analysis, put two rotating axis on principal axis and worktable respectively. Worktable rotates and it can clamp bigger work piece; principal axis swings and change direction of tool axis flexibly.

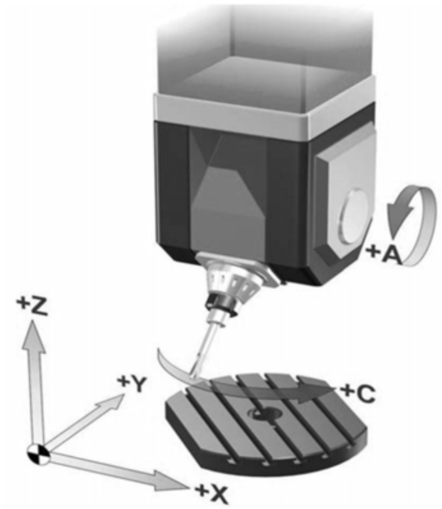

Fig. 12. Machine tool

5. Conclusion

Globoidal indexing cam is the main part of globoidal cam indexing mechanism, but its working surface is space non-developable surface, which affects design and manufacturing of globoidal indexing cam seriously and restricts the extensive application of globoidal cam indexing mechanism. The development of computer aided design provides a mature solution for the design of some complex surfaces and complex parts. This paper makes simulation for model of globoidal indexing cam as well as its design and processing based on UG8.0. The summary has been made as following: current research situation for design and manufacturing of current globoidal indexing cam has been described. Parameters of globoidal cam indexing mechanism have been analyzed and basic parameters have been confirmed. Common law of motion curve of globoidal indexing cam has been analyzed and its theoretical profile equation has been set up. Modeling method for globoidal indexing cam has been analyzed, model of globoidal indexing cam has been set up and serial design expansion has been made for it. Assembly of globoidal indexing cam has been established and operation simulation has been made. Processing method for globoidal indexing cam has been analyzed. The principle of five-axis CNC machine tool processing has been discussed. The adoption of processing technology of five-axis CNC machine tool as well as processing simulation has been confirmed.

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