DESIGN AND ANALYSIS OF CYLINDRICAL INDEXING CAM MECHANISM OF TOOL MAGAZINE IN MACHINING CENTER

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In order to realize the functions of smooth motion, accurate positioning and large carrying capacity during the tool change of the machining center drum type magazine, the mathematical model of the cylindrical indexing cam mechanism of the tool magazine is established by using the conjugate principle of the space envelope surface. The working contour data of the cylindrical indexing cam is obtained by calculation, and the cylindrical indexing cam is parametrically modeled by using NX software. The virtual prototype based on NX simulation module was established to perform kinematics and dynamics simulation analysis as well as output relevant characteristic curves. The simulation result data show that the design method of the cylindrical indexing cam mechanism is correct, which plays a guiding role in the further optimization design and manufacture of the mechanism.

Keywords: Cylindrical Indexing Cam; Drum Type Tool Magazine; Machining Center; NX

1. Introduction

CNC machining center is the mainstream and popular equipment of the current manufacturing industry [1, 2]. Its biggest feature is the tool storage and automatic tool change function, which is mainly realized by the tool magazine and automatic tool changer [3, 4]. At present, the tool magazine is a key functional component of the machining center, besides that its operating efficiency, motion stability and service life directly affect the overall performance of the machining center. Among the existing automatic tool changers, the cam type automatic tool changer is widely used in machining centers due to its high operating efficiency, low failure rate and stable operation [5]. The indexing cam working contour surface is a non-expandable curved surface, meanwhile its design and manufacture are more complicated. At present, there have been some researches on the design and manufacture of the indexing cam. Hsieh, J presents a simple yet comprehensive method for the design and machining of a cylindrical cam with a meshing indexing

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disc [6]. Yueming Zhang presents a complete and systematic method for the analysis and simulation of geometric characteristics of mating surfaces of globoidal cam mechanisms [7]. Hsieh proposes a simple yet comprehensive method for the design and analysis of an indexing cam mechanism with parallel axes [8]. Shuting Ji proposes a new approach: the analytical description of the globoidal cam rib-thickness is derived and calculated by using coordinate transformation, conjugate theory and differential geometry [9]. At present, researches on indexing cam mainly focus on the design of globoidal indexing cam, while the research on cylindrical indexing cam is especially less on its dynamics.

Therefore, this study takes the cylindrical indexing cam driven by the drum type magazine as the research object, uses the conjugate principle of the space envelope surface to establish the mathematical model of the cylindrical indexing cam, and calculates the working contour data of the cylindrical indexing cam. By using NX software to parametrically model the cylindrical indexing cam, it can create a virtual prototype of the mechanism. Finally, the output characteristic curve is analyzed by dynamic simulation to provide data reference for further structural optimization.

2. Methodology of design for rotary indexing mechanism

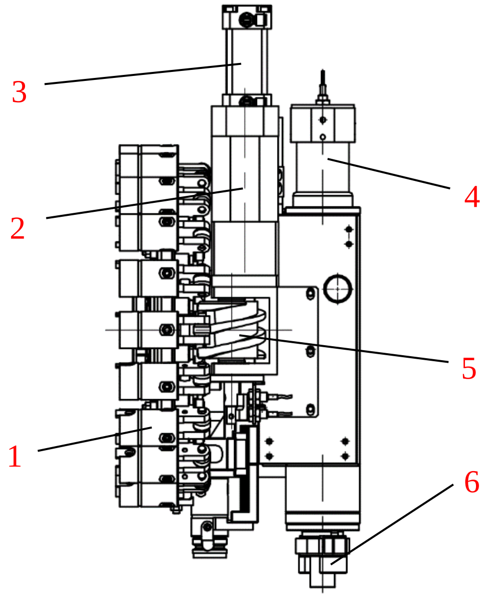
2.1 Analysis of tool change process in drum type tool magazine

The main part of the drum type magazine includes a tool plate assembly, a push tool cylinder, a tool arm drive motor, a tool plate drive motor, a cylindrical indexing cam, and a tool arm assembly, etc. The main part of the drum type magazine is as shown in Fig 1.

The following is a simple analysis of the tool change action of the drum type tool magazine.

(1) The spindle is stopped and moved to the tool change position;
(2) The tool plate is rotated to the selected tool position;
(3) The push tool cylinder is retracted to realize the push tool action;
(4) The tool arm rotates and holds the tool;
(5) The tool arm pulls out the tool and rotates 180 degrees;
(6) The tool arm lifts the tool to the tool holder and the spindle of the tool plate;
(7) The spindle and the tool holder lock the tool;
(8) The arm returns to the positioning position;
(9) The push tool cylinder is extended to return the tool holder to the positioning position.

During the entire tool change process, the push tool action is completed by the cylinder drive, and the speed is faster. Therefore, the efficiency of tool change is determined by the speed at which the magazine is indexed. It is necessary to select a suitable rotary indexing mechanism to improve the overall tool change efficiency, and ensure a smooth rotation process and accurate positioning [10].



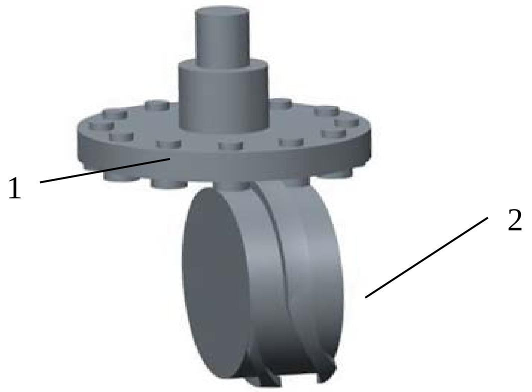
1. Tool plate assembly 2. Tool plate drives motor 3. Push tool cylinder
4. Tool arm drive motor 5. Cylindrical indexing cam 6. Tool arm assembly
Fig.1 The main part of the drum type magazine

2.2 Determination of the rotary indexing mechanism

The selection of the rotary indexing mechanism of the drum magazine mainly considers the operating efficiency, accuracy and stability of the tool magazine. At present, most of the drum type magazines use the Geneva mechanism, the worm gear mechanism, the globoidal indexing cam mechanism or the cylindrical cam indexing mechanism to realize the rotary indexing of the tool magazine.

The structure of the Geneva mechanism is simple, but because of its open structure, it is easy to stick to the object and affect the repeatability of the tool, meanwhile the tool change speed is slow. The worm gear mechanism can adjust the transmission gap of the worm gear at any time to achieve a more accurate indexing index, but the processing of the worm wheel and the worm are relatively difficult and relatively expensive. The transmission efficiency of the globoidal indexing cam mechanism and the cylindrical indexing cam mechanism is more than twice as high as that of the sheave mechanism. The load capacity of the mechanism is stronger, and the indexing index is more stable. It is suitable for the tool change mechanism with larger load. The cylindrical indexing cams are relatively simpler than globoidal indexing cams, and there are relatively few related studies. Therefore, the rotary indexing mechanism of the drum type magazine uses a cylindrical indexing cam mechanism [11].

The cylindrical indexing cam is a mechanism, which converts the continuous or periodic rotational motion of the cylindrical cam into intermittent rotation of the follower. The cam is cylindrical and as the active member, besides that the indexing plate is the follower. The indexing plate is provided with a plurality of rollers uniformly distributed in the circumferential direction, and the axis of the indexing plate is parallel to the axis of the roller and perpendicular to the axis of rotation of the cam. The schematic diagram of the mechanism is as shown in Fig 2 below.



1.Indexing plate 2.Cylindrical indexing cam
Fig.2 The cylindrical indexing cam mechanism

The working principle of the mechanism is as follows: the contour of the cylindrical indexing cam and the roller mesh with each other to realize the rotary indexing movement, meanwhile the contour of the cam is divided into an indexing section contour and a stop section contour. When the indexing section is working, it is externally meshing with the roller to drive the indexing plate to perform a rotary motion. When the contour of the stop section is working, the adjacent two rollers on the indexing plate are sandwiched on the ridge of the active cam, and the indexing plate stops moving, so that the indexing plate reaches the periodic stop motion.

2.3 Design and modeling of cylindrical indexing cam mechanism

The design and calculation of the cylindrical indexing cam mechanism are usually divided into several stages: the determination of the motion law of the indexing plate; the calculation of the main motion parameters of the mechanism; the calculation of the structural parameters of the cam mechanism; and the solution of the cam contour surface equation.

(1) Selection of the motion law of the indexing plate

The movements of the cylindrical indexing cam mechanism are only the rise section and the stop section, meanwhile there is no return section. Its motion curve always changes periodically according to the law of rise-stop-rise-stop. In the rise stage, the indexing plate realizes the stepping motion; in the stop stage, the indexing plate realizes the stopping motion. There is a gap between the surface of the indexing roller and the cam contour surface, besides that it is difficult to compensate; the offside impact is easy to occur during operation. Therefore, the cylindrical indexing cam mechanism is generally applied to medium speed, medium and light load applications.

We need to give priority to having a smaller maximum dimensionless acceleration and a maximum dimensionless saltus, and taking into account other characteristic values, when the motion law of the cylindrical indexing cam follower is selected. By comparing the characteristic values of several commonly used motion laws, the sinusoidal acceleration motion law meets the requirements. Therefore, the sinusoidal acceleration motion law is selected as the motion law of the cylindrical indexing cam mechanism follower.

The acceleration curve of the sinusoidal acceleration motion law is smooth and continuous without abrupt change. The velocity and acceleration at the beginning as well as end of the stroke are both 0; the midpoint of the stroke reaches the maximum value of the velocity; and the acceleration maximum occurs at 1/4 and 3/4 of the stroke. The saltus also varies within a limited range, which means that: the mechanism motion process does not produce a flexible impact; the start is smooth; and the impact load and wear are small.

(2) Calculation of the parameters of the cylindrical indexing cam mechanism

The basic parameters of the cylindrical indexing cam mechanism mainly include the number of threads, the number of rollers, and the number of divisions. The number of threads is generally expressed by H. We use a single thread H=1; the number of rollers is represented by z; the number of divisions is the number of times that the indexing plate needs to be stopped during 360 degrees of rotation, which is represented by I. The relationship between the three is that: I = z / H. The drum type magazine has a capacity of 24 tools, which means that: the number of division I=z=24; the cam type is a cam ridge type; and the rotation direction is a left-handed rotation.

Motion parameters of cylindrical indexing cam mechanism:

Active cam angular velocity: $\omega_1 = 2\pi n / 60 = \pi n / 30$

Active cam indexing angle: θ_f for tool magazine is generally 4π/3

Active cam stop angle: $\theta_d = 2\pi - \theta_f$

Indexing time: $t_f = \theta_f / \omega_1$

Stop time: $t_d = 2\pi / \omega_1 - t_f$

Indexing plate indexing angle: $\phi_f = 2\pi / I = \pi / 12$

Indexing plate indexing angular displacement: $\phi_i = S\phi_f$

(Sinusoidal acceleration law: S=T-sin2πT/2π)

Indexing plate indexing angular velocity: $\omega_2 = \phi_f V / t_f = \phi_f \omega_1 V / \theta_f$

(Sinusoidal acceleration motion law: V=1-cos2πT)

Ratio of indexing plate to cam angular velocity: $\omega_2 / \omega_1 = \phi_f V / \theta_f$

Motion-stand ratio: $k = t_f / t_d$

Geometric dimensions of the cylindrical indexing cam mechanism:

Center distance: C is determined by the overall design dimensions of the drum magazine.

Base distance: A is the vertical distance between cam axis and end surface of the indexing plate.

Allowable pressure angle: α_p=30°~40°

Indexing plate circle pitch radius: $r_{P2} \approx 2C / [1 + \cos(\phi_f / 2)]$

Cam pitch circle radius: $r_{P1} \geq \phi_f V_{max} r_{P2} / \theta_f \tan\alpha_P$

Roller radius: $r_0 = (0.4 \sim 0.6) r_{P2} \sin(\pi / z)$

Roller width: $b = (1.0 \sim 1.4) r$

The gap between the roller and the bottom of the cam groove: $e = (0.2 \sim 0.3) b$

Cam positioning torus radial depth: $h = b + e$

Cam positioning torus outer diameter: $D_0 = 2r_{P1} + b$

Cam positioning torus inner diameter: $D_1 = D_0 - 2h$

Indexing plate outer diameter: $D_2 \geq 2(r_{P2} + r_0)$

Indexing plate width: B_2 is selected according to actual needs.

Cam width: $2r_{P2} sin(\pi / z) < l < 2r_{P2} sin(\pi / z) + 2r_0$

The cylindrical indexing cam motion parameters and geometric parameter values are listed in Table 1 below:

Table1

Cylindrical indexing cam motion and geometric parameters

Parameters	Value
Number of division /I	24
Number of threads /H	1
Active cam angular velocity /ω_1	10π/3
Active cam indexing angle /θ_f	4π/3
Active cam stop angle /θ_d	2π/3
Indexing time /t_f	0.4s

Stop time /t_d	0.2s
Indexing plate indexing angle /$\emptyset_f$	π/12
Movement rule of turntable indexing period	Sinusoidal acceleration
Motion-stand ratio /k	2
Center distance /C	145mm
Base distance /A	61mm
Allowable pressure angle /α_p	32°
Indexing plate circle pitch radius /r_{P2}	146mm
Cam pitch circle radius /r_{P1}	44mm
Roller radius /r_0	8mm
Roller width /b	8mm
Gap between roller and cam groove bottom /e	3mm
Cam positioning torus radial depth /h	11mm
Cam positioning torus outer diameter /D_0	96mm
Cam positioning torus inner diameter /D_1	74mm
Indexing plate width /B_2	10mm
Cam width /l	40mm

(3) Solution of cylindrical indexing cam contour surface equation

The working contour surface of the cylindrical indexing cam mechanism is a space non-expandable curved surface, which is difficult to measure and cannot be designed by using the method of unfolding into a plane profile. Generally, the design is calculated according to the conjugate principle of the space envelope surface.

(4) Selection of coordinate system

By using the conjugate principle of the envelope surface, four sets of reference coordinate systems are established to obtain the discrete coordinate values of the working contour of the cylindrical indexing cam. The four sets of coordinate systems are: the fixed coordinate system $O_0X_0Y_0Z_0$ connected to the base; the fixed coordinate system $O_0'X_0'Y_0'Z_0'$ connected to the base; the moving coordinate system $O_1X_1Y_1Z_1$ connected to the cylindrical indexing cam; the moving coordinate system $O_2X_2Y_2Z_2$ connected to the indexing plate. The above coordinate system is as shown in Fig 3.

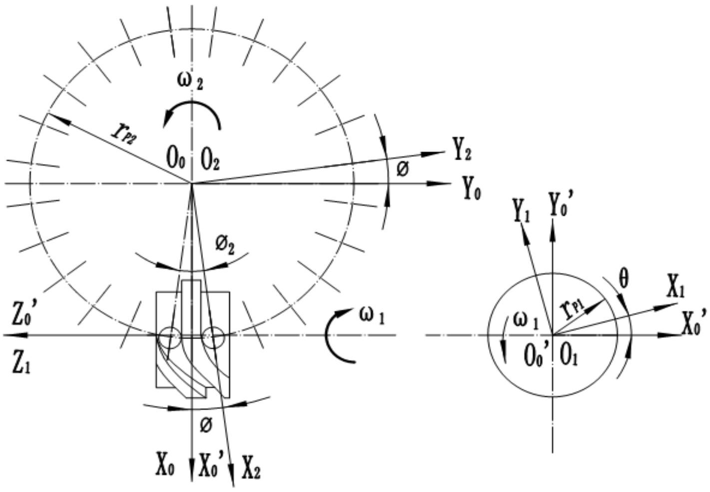


Fig.3 The coordinate system of cylindrical indexing cam

(5) Cylindrical indexing cam contour equation

The equation for the indexing roller cylindrical surface in $O_2X_2Y_2Z_2$ is:

$$\begin{cases} x_2 = r_{P2} + r_0 cos\varphi \\ y_2 = r_0 sin\varphi \\ z_2 = -r \end{cases} \tag{1}$$

In equation (1): r, φ are the surface parameters of cylindrical working surface equation of roller.

The conjugate contact equation between the roller and the cam is:

$$\cot\varphi = p\left[\frac{r_{P2}}{(A-r)\cos\phi}\left(\frac{\omega_2}{\omega_1}\right) - \tan\phi\right] \tag{2}$$

In equation (2): the cam is left-lateral, when p=1； and the cam is right-lateral， when p=-1; Ø is the angle between the indexing roller axis O_2Y_2 and O_0Y_0.

The equation for the cam working contour in $O_1X_1Y_1Z_1$ is:

$$\begin{cases} x_1 = (x_2\cos\phi + py_2\sin\phi - C)cos\theta + (z_2 + A)\sin\theta \\ y_1 = (-x_2\cos\phi - py_2\sin\phi + C)sin\theta + (z_2 + A)cos\theta \\ z_1 = px_2\sin\phi - y_2\cos\phi \end{cases} \tag{3}$$

In equation (3): the cam is left-lateral， when p=1； and the cam is right-lateral， when p=-1; C is the center distance; A is the base distance; θ is the cam angle; Ø is the angle between the indexing roller axis O_2Y_2 and O_0Y_0 (the position angle of the roller).

The three-dimensional coordinate values of the working contour of the cylindrical indexing cam in the moving coordinate system are obtained by simultaneously solve the above three sets of nonlinear equations.

(6) Parametric modeling of cylindrical indexing cam mechanism based on NX

NX is an interactive CAD/CAE/CAM software system that is powerful enough to easily construct a variety of complex parametric entities and models, as well as kinematics and dynamics simulation of related models [12]. It has been widely used by multidisciplinary researchers.

According to the basic parameters of the cylindrical indexing cam mechanism and the previously determined driven indexing plate movement law curve as well as the flow chart shown in Fig 4 below, the point cloud data of the cam working contour can be obtained by NX.

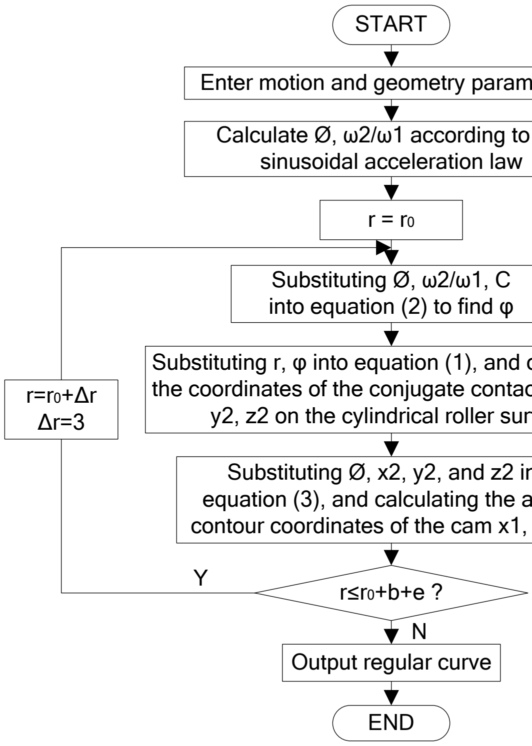
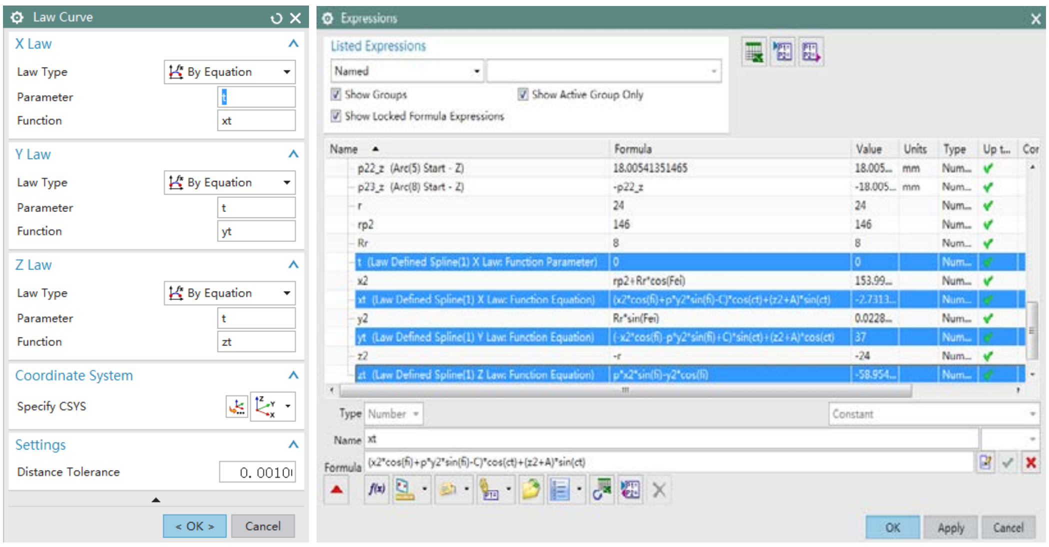


Fig.4 The flow chart of cam working contour point cloud data calculation

From the above chart, when the corresponding cam angle $\theta_f \leq \theta \leq 2\pi$, it is the stop period of the indexing plate; the angular displacement $\emptyset_i=0$; and the angular velocity ratio $\omega_2/\omega_1=0$. At this time, the working contour of the cam is the positioning torus. The point cloud coordinate values can be obtained by substituting equations (1), (2), and (3) for $\emptyset=p\emptyset_f/2$, when $\theta=0$ or $\emptyset=-p\emptyset_f/2$; when $\theta=\theta_f$.

The modeling process is as follows: We use the isometric surface method to model cylindrical cams. Firstly, the cam geometry and motion parameters are entered into the NX software in the form of expressions.

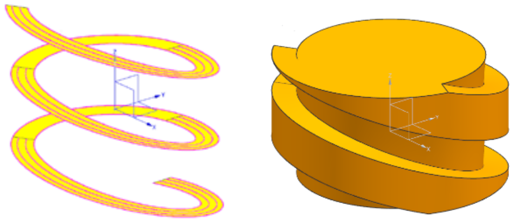
Then we use NX's "Law curve" - "By Equation"(Fig 5a), with the NX system independent variable "t"(shown in Fig 5b by expressions) as the independent variable, and "xt, yt, zt" (shown in Fig 5b by expressions) as the dependent variable to establish multiple contour curves corresponding to different r values.



a b

Fig.5 The geometric parameters and motion parameter input interface in NX

Finally, the "through curve" function is used to create cam contour surfaces of multiple curves, as shown in Fig 6a below. We create a cylinder as the base of the cylindrical indexing cam, and thicken the surface into a solid one, meanwhile the thickness is the diameter of the roller. Then, the thickened solid and the cylindrical base are subjected to the difference of the matte to remove the excess material to obtain the cylindrical indexing cam entity. The cylindrical indexing cam model is as shown in Fig. 6b.



a b

Fig.6 The working contour surface and cam solid of cylindrical indexing cam

The cylindrical indexing cam and the indexing roller are added to the constraints to complete the assembly, besides that the total assembly drawing of the mechanism is as shown in Fig. 7 below.

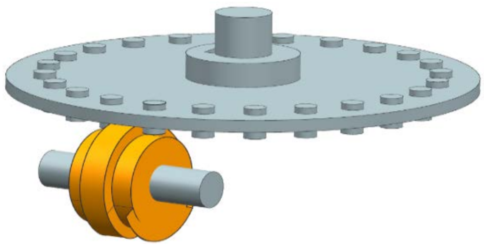


Fig.7 The assembly model of cylindrical indexing cam mechanism

3. Methodology of dynamic simulation analysis for cylindrical indexing cam mechanism

3.1 Construction of virtual prototype of cylindrical indexing cam mechanism

We need to build a virtual prototype in the NX modeling environment. Firstly, we make necessary simplifications to the assembly model, then remove excess parts, and retain only the necessary parts such as cylindrical indexing cams, turntables and rollers. Quality information is defined for each part of the mechanism: 20CrMnTi steel for the cam material and 45# steel for other materials. Secondly, we enter the NX motion simulation module, create a new simulation and choose the analysis type as dynamics.

In combination with the actual movement of the cylindrical indexing cam mechanism with the drum magazine, the following constraints are added to the cylindrical indexing cam mechanism: adding a revolute joint between the ground and the cam; adding a revolute joint between the ground and the indexing plate; adding a revolute joint between the rollers and the indexing plate. At the same time, a rotary driver is added to the cam revolute joint at a speed of 100 rev/min; a 3D contact is added between the rollers and the cam contour surface; the contact stiffness of the 3D contact is set to 600000 N/mm; the force exponent is 1.5; and the material damping is 60 N-sec/mm. Through the above operations, the virtual prototype creation of the cylindrical indexing cam mechanism is completed.

3.2 Results and discussion of dynamic simulation analysis

We create a new solution in the NX motion simulation environment, in which the solution is set as: the simulation time is set to 1.3s; the number of steps is 200; the gravity constant is added; and the direction of gravity is selected as the cam axis (the gravity direction of the magazine). The simulation results of the cylindrical indexing cam mechanism can be obtained by submitting the solution. In the results, you can view the animation and draw the angular displacement, angular velocity, and angular acceleration curve of the indexing plate as shown in Fig 8. The contact force curve between the cam and the roller is as shown in Fig 9.

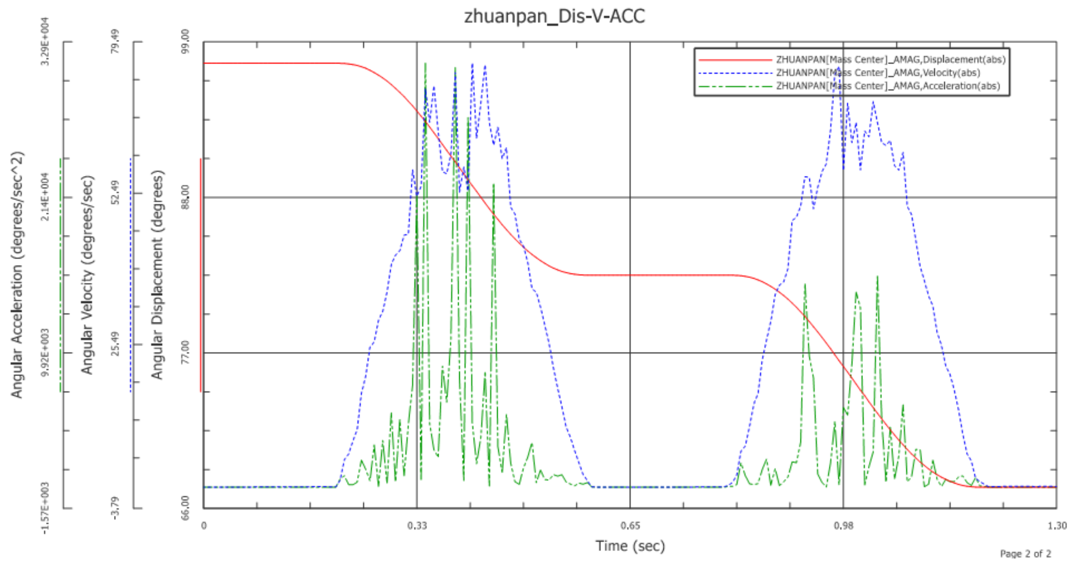


Fig.8 The curve of angular displacement, angular velocity and angular acceleration of indexing plate

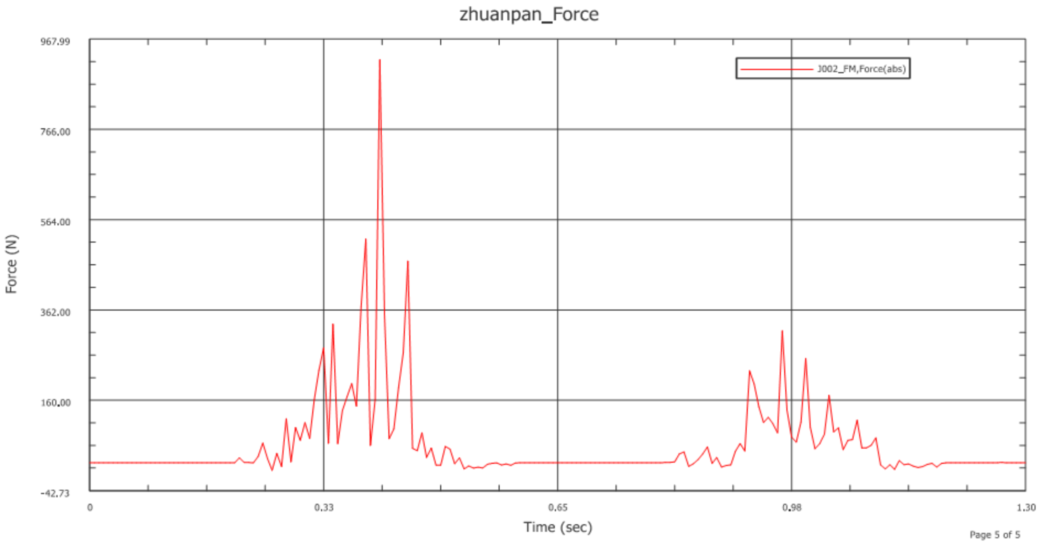


Fig.9 The contact force curve between cam and roller

(1) In Fig. 8, the red curve is an angular displacement curve; the blue curve is an angular velocity curve; and the green curve is an angular acceleration curve. By comparison, we can see that the angular velocity and angular acceleration of the indexing plate are linearly related; the angular acceleration of the indexing plate in the stop period approaches 0, which verifies the correctness of the model design. Because of the influence of the contact parameters, the angular acceleration value in the indexing period has abruptly changed during the collision process.

(2) In Fig. 9, the contact force between the cam and the roller approaches the zero in the stop period, and the peak of the contact force appears in the indexing period, which again verifies the correctness of the model.

4. Conclusion

In this study, the cylindrical indexing cam mechanism for rotary indexing of drum type magazines was designed. The parametric modeling was completed by obtaining the working contour data of the cylindrical indexing cam, and finally the virtual prototype of the mechanism was built as well as the dynamic simulation analysis was completed. The simulation results verify the correctness of the design model, and provide an important reference for the subsequent improvement design research.

In the next stage, we will study the machining and assembly process of the cylindrical indexing cam and test the dynamic performance of the cylindrical indexing cam mechanism under actual working conditions to further optimize the rotary indexing mechanism.

Acknowledgements

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