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Design Method of Cam Five-bar Paper Picking Mechanism of Packaging Machine Based on Position and Orientation Constraints

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The work aims to present a design method of cam five-bar paper taking mechanism of packaging machine based on position and orientation constraints to better meet the position and orientation requirements of the end paper taking actuator in the high-speed paper picking process. At the first stage, according to the given ideal position and orientation requirements of the end paper taking actuator, the mathematical model of the five-bar mechanism satisfying the position and angle constraints is established by using the kinematic mapping theory, and two cams are used to constrain the two freedom of the five-bar mechanism to obtain the cam five-bar paper taking mechanism. At the next stage, the relationship between the five-bar mechanism and the cam angle under the given position and angle constraints is solved, and the theoretical profile of the cam is established by using cubic spline curve function. Finally, the whole paper taking mechanism is optimized to obtain the best mechanism parameters. Through the design example of the cam five-bar mechanism of the high-speed packaging machine, it is verified that the designed value taking mechanism can accurately realize the given orientation point, and there is no contour distortion of the cam. This method can not only realize the given position and orientation of the end actuator, but also further optimize cam profile of the paper taking mechanism to improve the running stability and accuracy.

Keywords: Paper picking mechanism, double cam, five-bar, Position and orientation

1 Introduction

In the packaging industry, the paper packaging industry contributes the most to the total output value, and the act of paper extraction is a crucial function. The primary function of the paper take-out mechanism is to extract the paper chips from the paper bin of the high-speed packaging machine and to place them steadily on the conveyor belt [1]. Gao Xu [2] designed the paper taking mechanism by combining two cams with a five-bar mechanism. And the cam profile was determined using analytical formulas and graphical methods. Based on the analysis of the position and attitude of the paper taking actuator, Yang Benben [3] et al. proposed a dual cam four-bar paper taking mechanism, and constructed the cam equation of the paper taking mechanism using the combination of polynomials and circular arc segments.

Currently, the paper-picking mechanism primarily utilizes a cam and a five-bar linkage mechanism. This design uses two cams to constrain the degrees of freedom in the motion of the five-bar linkage, successfully implements the expected motion patterns of the actuator as described in reference [4]. However, the structural design of the entire machine primarily utilizes the traditional mechanical parameters optimization methods, which have some defects: 1) To achieve the expected position and posture of the actuator, the design of the two cam profiles used to drive the five-bar linkage often exhibits a concave phenomenon, compromising the stability and accuracy of the mechanism's operation. 2) These traditional methods cannot directly optimize the design of the five-bar linkage to meet specific position and posture requirements [5]. Therefore, after analyzing the process requirements for paper picking, this study introduces a design method for a cam and five-bar paper-picking mechanism that meets position and posture constraints. Utilizing kinematic mapping theory, a mathematical model for the five-bar linkage is established, ensuring compliance with position and posture constraints. By constraining two degrees of freedom in the five-bar linkage using cam profiles, a cam and five-bar mechanism is constructed, and the final mechanical parameters are determined. This method not only precisely achieves the desired position and posture of the end actuator, but also meets the additional process requirements of high-speed packaging machines through further optimization of the mechanism.

2 Material and Research Method

2.1 Process Analysis and Mechanism Solving Approaches

As shown in Fig. 1 for high-speed packaging machine paper-picking mechanism ideal process: paper-picking actuator in the packaging machine close to the paper bin, it needs to maintain and the paper bin parallel posture, in order to facilitate the realization of the suction cup pick-up action; exit the pick-up position for a period of time is also required to maintain a parallel posture to avoid picking up the paper in the process of the actuator swinging and the occurrence of interference; Finally, the actuator must maintain a parallel state with the conveyer belt and ensure a consistent speed at the paper placement position.

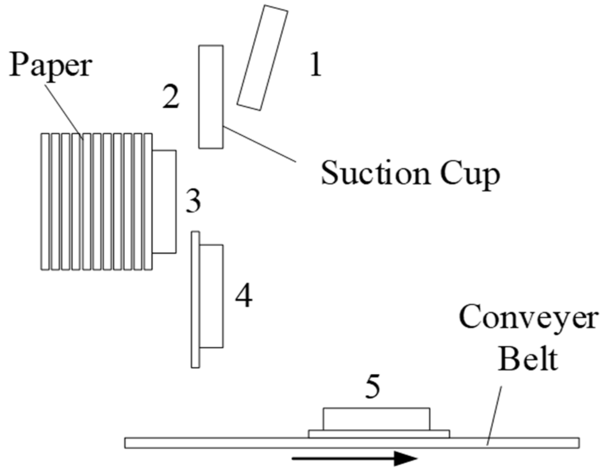

Fig. 1 *Ideal technological process of paper taking mechanism*

In this article, a double cam five-bar mechanism is employed to achieve the ideal process of the paper-picking mechanism. Fig. 2 displays the structural diagram. The main cam (1) and the sub cam (2) are the two cams that are affixed to the frame. The five-bar mechanism (3) comprises a parallelogram and a 2R bar group, which is equivalent to a 3R bar group with three degrees of freedom. This article discusses a single degree of freedom cam five-bar mechanism that is formed when two degrees of freedom are constrained by two cams, aimed at meeting the process requirements of high-speed packaging machines.

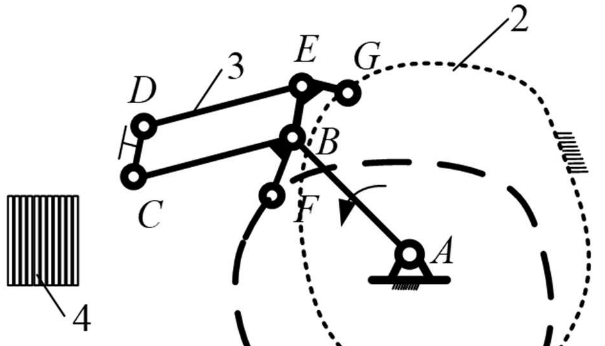

Fig. 2 *Structure diagram of double cam five bar paper taking mechanism*

Where:
1…Main cam,
2…Sub cam,
3…Five-bar mechanism,
4…Paper bin.

The working principle of the mechanism is as follows: the five-bar mechanism (3) is driven by the motor to execute a circular motion, and the two cams constrain the mechanism's two degrees of freedom to achieve the position and attitude required by the end actuator, in order to meet the process requirements of the high-speed picking up process of the packaging machine. The key challenge is to accurately achieve the designated position and attitude of the end actuator through mechanical design methods. This article selects the position and attitude points of the end actuator at the key positions of paper picking, and uses the kinematics mapping theory to establish a mathematical model of the five-bar mechanism that adheres to position and attitude constraints. The cam and five-bar paper picking mechanism is obtained by constraining the two degrees of freedom of the five-bar mechanism with the cam profile. The position and attitude of the end actuator are mainly achieved by two parts of action: one is the swing of the rod *BC* relative to the rod *AB*, and the other is the swing of the rod *CD* relative to the rod *BC*. In order to accurately achieve the position and attitude requirements of the given key points, the solution idea is to first give the four key position and attitude points of the rod *CD* during the paper picking process and the motion law of the cam (2), and determine the specific position and attitude points of point *C*. Taking the position and attitude points of point *C* as constraints, a mathematical model of the 2R rod group is established using the kinematics mapping theory, and the curves of the hinge point *A* and hinge point *B* are solved. According to the requirements of the mechanism transmission, the optimal mechanism parameters are selected. The specific process is shown in Fig. 3.

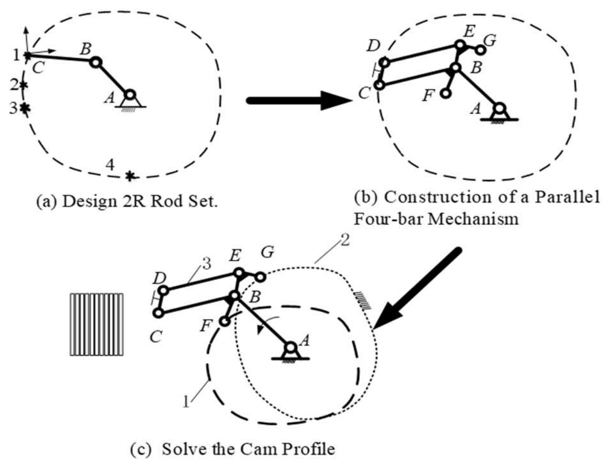

Fig. 3 *Solution of double cam five bar paper taking mechanism*

2.2 Design method of five-bar mechanism for position and posture requirements

The point Q on the rod BC in the five-bar mechanism that meets the position and attitude requirements can be considered as a point (x, y) moving (d_1, d_2) and rotating by an angle φ in the dynamic coordinate system oxy fixed to the rod BC. The coordinates of point Q in the static coordinate system OXY are:

$$\begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\varphi & -\sin\varphi & d_1 \\ \sin\varphi & \cos\varphi & d_2 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{1}$$

The inverse operation can be obtained as follows:

$$\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} \cos\varphi & \sin\varphi & -d_1\cos\varphi - d_2\sin\varphi \\ -\sin\varphi & \cos\varphi & d_1\sin\varphi - d_2\cos\varphi \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} \tag{2}$$

According to the kinematic mapping theory [6-10], the method for solving the problem of a given position point uses homogeneous coordinates (Z_1, Z_2, Z_3, Z_4) represented by four elements to represent the position and attitude coordinates of point Q (d_1, d_2, φ).

$$\begin{cases} Z_1 = 0.5(d_1\sin(0.5\varphi) - d_2\cos(0.5\varphi)) \\ Z_2 = 0.5(d_1\cos(0.5\varphi) + d_2\sin(0.5\varphi)) \\ Z_3 = \sin(0.5\varphi) \\ Z_4 = \cos(0.5\varphi) \end{cases} \tag{3}$$

It can be obtained as follows:

$$\begin{cases} \sin\varphi = \dfrac{Z_4^2 - Z_3^2}{Z_3^2 + Z_4^2} \\ \sin\varphi = \dfrac{2Z_4Z_3}{Z_3^2 + Z_4^2} \\ d_1 = \dfrac{2(Z_1Z_3 + Z_2Z_4)}{Z_3^2 + Z_4^2} \\ d_2 = \dfrac{2(Z_2Z_3 - Z_1Z_4)}{Z_3^2 + Z_4^2} \end{cases} \tag{4}$$

Substituting Eq.4 into Eq.1 yields:

$$\begin{bmatrix} X \\ Y \\ 1 \end{bmatrix} = \begin{bmatrix} Z_4^2 - Z_3^2 & -2Z_4Z_3 & 2(Z_1Z_3 + Z_2Z_4) \\ 2Z_4Z_3 & Z_4^2 - Z_3^2 & 2(Z_2Z_3 - Z_1Z_4) \\ 0 & 0 & Z_3^2 + Z_4^2 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{5}$$

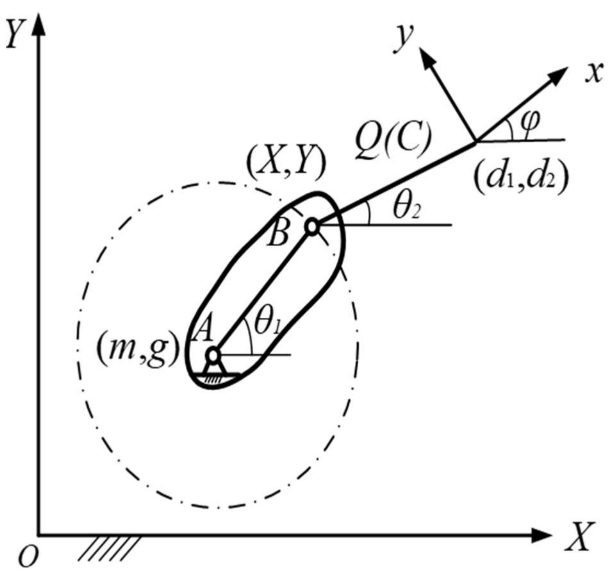

***Fig. 4** The moving point on the bar AB is constrained to a circle*

By utilizing the coordinate system mapping relationship described above for the rigid body motion process, a coordinate system is established as illustrated in Fig. 4. That system is positioned on the rods BC and AB of the five-bar mechanism. In that coordinate system, the center point B (X, Y) is restricted to a circle that has A (m, g) as its center and has a radius of R_{AB}. Hence, the trajectory of this point can be depicted by the general equation of a circle:

$$c_0(X^2 + Y^2) + 2c_1X + 2c_2Y + c_3 = 0 \tag{6}$$

Where:

c_0 , c_1 , c_2 and c_3 …Specific parameters of this equation and c_0 is not zero, otherwise the trajectory is not circular.

In order to find the appropriate point A and point B in the 2R rod set, substitute the coordinates (X, Y) of point B into Eq.6 and simplify to obtain:

$$\begin{aligned} &2c_0(Z_1^2 + Z_2^2) - 2c_0x(Z_1Z_3 - Z_2Z_4) - 2c_0y(Z_2Z_3 + Z_1Z_4) + \\ &2c_1(Z_1Z_3 + Z_2Z_4) + 2c_2(Z_2Z_3 - Z_1Z_4) + 2(c_2x - c_1y)Z_3Z_4 \\ &-(c_1x + c_2y)(Z_3^2 - Z_4^2) + (c_3 + c_0x^2 + c_0y^2)(Z_4^2 + Z_3^2)/2 = 0 \end{aligned} \tag{7}$$

By arranging the coefficients in the equation, it can be obtained as follows:

$$\begin{cases} q_1 = 2c_0, q_2 = -2c_0 x \\ q_3 = -2c_0 y, q_4 = 2c_1 \\ q_5 = 2c_2, q_6 = 2(c_2 x - c_1 y) \\ q_7 = -(c_1 x + c_2 y) \\ q_8 = 0.5(c_3 + c_0 x^2 + c_0 y^2) \end{cases} \tag{8}$$

Organising the intrinsic relationship of Eq.8 leads to the following relational expression:

$$\begin{cases} q_1 q_6 + q_2 q_5 - q_3 q_4 = 0 \\ 2q_1 q_7 - q_2 q_4 - q_3 q_5 = 0 \end{cases} \tag{9}$$

From Eq. 8 and the geometric relationship of the 2R rod set:

$$\begin{cases} x = \dfrac{(q_6 q_5 - 2q_7 q_4)}{(q_5^2 + q_4^2)} \\ y = \dfrac{-(q_6 q_4 + 2q_7 q_5)}{(q_5^2 + q_4^2)} \end{cases} \tag{10}$$

$$\begin{cases} m = \dfrac{c_1}{c_0} = \dfrac{(q_6 q_3 + 2q_7 q_2)}{(q_2^2 + q_3^2)} \\ g = \dfrac{c_2}{c_0} = \dfrac{2(-q_6 q_2 + 2q_7 q_3)}{(q_2^2 + q_3^2)} \end{cases} \tag{11}$$

Therefore, when given the coordinates of n points within a planar coordinate system containing position and attitude requirements, their coordinates (d_{1i}, d_{2i}, φ_i) (i = 1, 2, 3.... .n) into Eq.7, a system of linear equations can be obtained:

$$Aq = \begin{bmatrix} A_{11} & \cdots & A_{18} \\ \vdots & \ddots & \vdots \\ A_{n1} & \cdots & A_{n8} \end{bmatrix} \begin{bmatrix} q_1 \\ \vdots \\ q_8 \end{bmatrix} = 0 \tag{12}$$

Among them: $A_{i1} = Z_{i1}^2 + Z_{i2}^2$, $A_{i2} = Z_{i1}Z_{i3} - Z_{i2}Z_{i4}$, $A_{i3} = Z_{i2}Z_{i3} + Z_{i1}Z_{i4}$, $A_{i4} = Z_{i1}Z_{i3} + Z_{i2}Z_{i4}$, $A_{i5} = Z_{i2}Z_{i3} - Z_{i1}Z_{i4}$, $A_{i6} = Z_{i3}Z_{i4}$, $A_{i7} = Z_{i3}^2 - Z_{i4}^2$, $A_{i8} = Z_{i3}^2 + Z_{i4}^2 \, (i = 1 \cdots n)$.

By solving the parameters in Eq. 12, the final mechanism parameters that meet the given position and attitude requirements can be obtained. It can be seen from the above expression that the problem is a least-squares optimal fitting problem solved through the matrix of linear system of equations at $n \times 8$. For the solution of this question, it is mainly through Gaussian elimination method, singular value decomposition (SVD) algorithm and so on. In order to obtain the rod *AB* and rod *BC* that meet the requirements for the given position and attitude, this article uses the singular value decomposition (SVD) algorithm to solve the curves of points *A* and *B*. The specific solution process can be found in references [10, 11]. According to the relevant theories for solving the problem of positioning and orienting a given point [11, 12], when the positions and orientations of four points are given, the resulting 2R rod set can accurately achieve the position and orientation of the given point. When the positions and orientations of five or more points are given, the resulting 2R rod set can only approximately achieve the position and orientation of the given points [13, 14].

2.3 Mathematical modelling of the kinematics of the double cam profile

By establishing and solving the kinematic mapping of the five-bar mechanism, the rods *AB* and *BC* that meet the requirements for the given position and attitude points can be obtained, and the angle between the rods *BC* and *CD* at the given position can be determined. According to the specific structure of the cam five-bar paper picking mechanism, the swinging law of the rods *CD* and *BC* is achieved by the motion law of the two cams. Thus, this article first establishes the kinematic law of the two rods based on the angle between rod *BC* and rod *CD* at a given position, and employs the cubic spline curve method for fitting key angle points, establishing the swinging law of *CD* and rod *BC* [15-19]. Ultimately, the cam profile is obtained, and the overall mechanical parameters are determined.

According to the design method of cam profile [9-10], the coordinates of the theoretical profile of the cam are:

$$\begin{cases} x = a\sin\delta - l\sin(\delta + \beta + \beta_0) \\ y = a\cos\delta - l\cos(\delta + \beta + \beta_0) \end{cases} \tag{13}$$

Where:

a…The distance from the center of the cam base circle to the rotation center of the pendulum rod,

δ…Rotation angle of the cam,

β_0…The initial angle of the pendulum rod,

β…The angle at which the pendulum rod turns relative to the cam as it turns through the angle δ.

Since the distance between the actual profile and the theoretical profile of the cam in the normal direction is equal to the radius of the roller, when any point $F(x, y)$ on the theoretical profile is known, the corresponding point on the actual working profile can be obtained by taking the distance r_t along the theoretical profile in the direction of the normal to the point $F'(x', y')$:

$$\begin{cases} x' = x \mp r_t \cos\alpha \\ y' = y \mp r_t \sin\alpha \end{cases} \tag{14}$$

Where:

$\sin\alpha = \dfrac{(dx/d\delta)}{\sqrt{(dx/d\delta)^2 + (dy/d\delta)^2}}$,

$\cos\alpha = -\dfrac{(dy/d\delta)}{\sqrt{(dx/d\delta)^2 + (dy/d\delta)^2}}$,

"-"…Denotes the actual profile inside the cam,
"+"…Denotes the actual profile outside the cam.

3 Results and Analysis

In order to verify the design method of cam five-bar paper pickup mechanism for high-speed packaging machine based on position and posture constraints proposed in this article, and to design a satisfactory paper picking mechanism according to the relevant requirements, a specific mechanism example design was conducted in conjunction with the relevant literature [1] and the requirements related to the paper picking process. Firstly, based on the requirement for the end-effector to maintain parallelism with the paper storage, three key positions and posture points were selected. Secondly, according to the requirement that the end actuator needs to remain parallel to the drive belt when releasing paper, one key position and attitude point was selected. Considering the size of the roller radius and the space of the subsequent installation dimensions, the rod *DC* is set to 40mm, and the swing angles at the given four key points are [7°, 0°, -8°, 0°], The specific data of the four positions and posture points of the paper-picking mechanism at point *C* are shown in Tab. 1.

***Tab. 1** Four key positions and orientations of the paper picking mechanism*

position and attitude	1	2	3	4
X(mm)	-274	-280	-275	0
Y(mm)	19.7	0	-13	-280
φ (°)	97	90	82	180

According to the above five-bar mechanism design method, the position and attitude parameters of the four points in Table 1 are firstly expressed in four-element homogeneous coordinates (Z_1, Z_2, Z_3, Z_4) and the following coefficient matrices are obtained by using Eq.12:

$$A = \begin{bmatrix} 18866 & -26.473 & -134.778 & -137 & 9.85 & 0.4963 & 0.1219 & 1 \\ 19600 & 0 & -140 & -140 & 0 & 0.5 & 0 & 1 \\ 18948.5 & 25.573 & -135.257 & -137.5 & -6.5 & 0.4951 & -0.1391 & 1 \\ 19600 & 0 & -140 & 0 & -140 & 0 & 1 & 1 \end{bmatrix} \tag{15}$$

Based on the above coefficient matrix, the eigenvalues (shown in Tab. 2) and corresponding eigenvectors of this coefficient matrix are obtained using the singular value decomposition (SVD) algorithm. The problem of solving the specific coordinates of the hinge points *A* and *B* is a least squares problem, and the eight eigenvalues in Tab. 2 reflect the least squares fitting error. The eigenvalues are 0 then the corresponding eigenvectors form a system of linear equations pass must be satisfied with the system of equations. According to Eq. 9, it is known that there are two unrelated constraint relations for the 2R rod set of the double rotating vice, and the solution space should be:

$$q = \alpha v_1 + \beta v_2 + \gamma v_3 + \kappa v_4 \tag{16}$$

Where:

v_1, v_2, v_3, v_4…The eigenvectors corresponding to the four zero eigenvalues obtained from the solution,

α, β, γ, $\varkappa$ are the vector coefficients.

To obtain all the solution values within the global range, it can be made that $\kappa = \cot(\omega) \quad \omega \in (0, \pi)$, each of which can be selected to get up to four sets of specific solution values for point *A* and point *B*. The final shape to the curves of points *A* and *B* in the rod *AB* is shown in Fig. 5.

***Tab. 2** Features corresponding to given 4 positions and angle points*

Serial number	1	2	3	4	5	6	7	8
Eigenvalue	0	0	0	0	0.1458	1416.6	29667.2	1.483×10^6

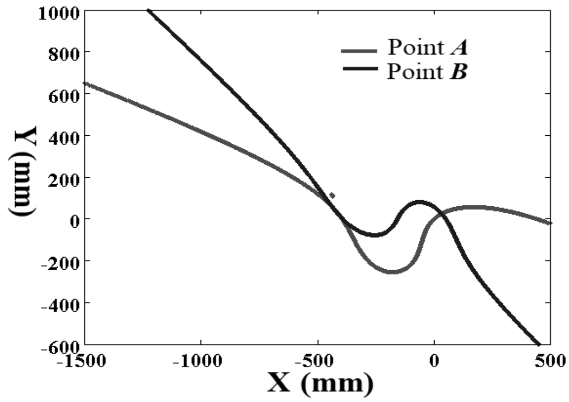

Fig. 5 *Curve of points A and B*

In order to construct the optimal five-rod paper picking mechanism by selecting the appropriate mechanism parameters from the global solution values, the rod length *AB is* restricted to the range of [80,180] and the rod length *BC* is limited to the range of [80,160], taking into account the process-specific requirements of the related literature [1]. For this purpose, the feasible regions of hinge point *A* and hinge point *B* shown in Fig. 6 were finally obtained.

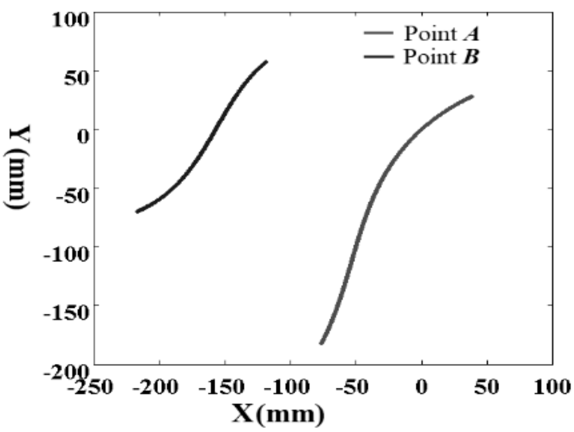

Fig. 6 *Feasible regions of points A and B*

When the specific coordinates of hinge *A* and hinge *B* are obtained, the specific parameters of the whole double cam five-bar mechanism can be obtained, and the turning angles of rod *BC* and rod *DC* at the given four key points are obtained, the cam motion law is established by the cubic spline curve, and the final cam profile is constructed from the kinematic mathematical model of the two cam profiles. For this purpose, in this article, the hinge *A* of the first group is selected as (0.04,0.04), and the hinge point *B* is (-136.04,36.97), and the hinge point *A* of the second group is selected as (-25.5,-108.69), and the hinge point *B* is (-177.75,-35.78), and with the help of the powerful computational ability of the MATLAB software and the graphical display content, we obtained the final double-cam five-bar mechanism, as shown in Fig. 7 and Fig. 8.

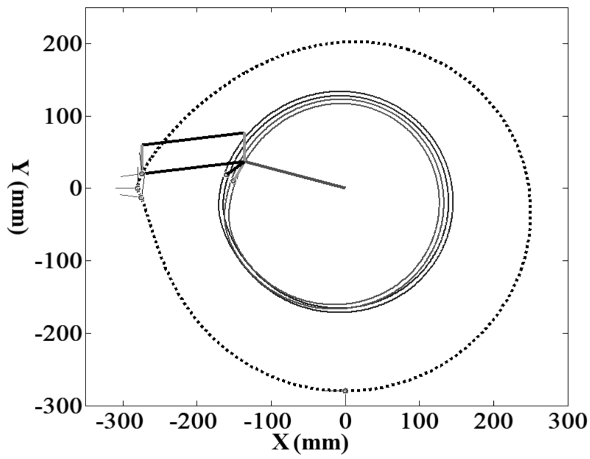

Fig. 7 *Final double cam five bar mechanism of the first set of data*

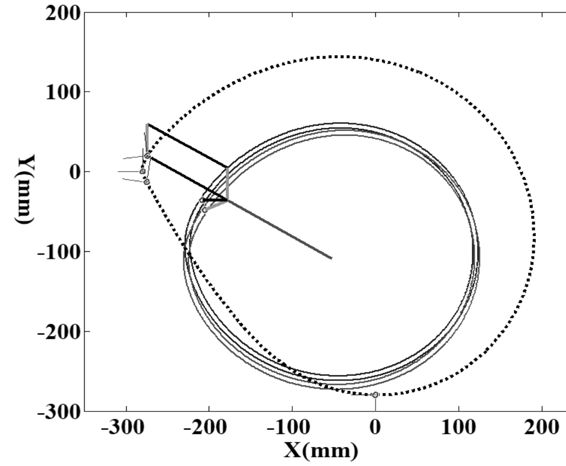

Fig. 8 *Final double cam five bar mechanism of the second set of data*

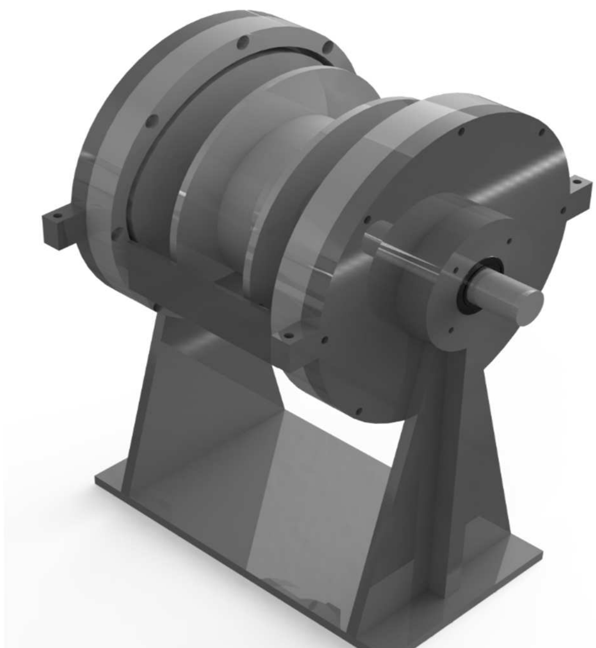

Fig. 9 *Three-dimensional model of the final double-cam five-bar mechanism*

From the trajectories of the above two groups of data, it can be seen that in the second group of trajectories, the rod *DC* can be disengaged from the paper pickup position faster, which can avoid the occurrence of the relevant actuator interference. At the same time, the two cams in the second set of trajectories do not exist in the concave area, which can better meet the requirements of the actual working conditions. Therefore, this article selects the specific parameters of the second group of data to design the relevant structure. In the structural design, the two cam groups were fixed on the left and right sides of the frame, the rod *AB* is made into a disc and driven through the spindle, the other rods are designed as connecting rods according to the given parameter requirements, and the rod *DC* is designed as a long strip plate with hinge. The related 3D structure was designed using 3D software, as seen in Fig. 9 below.

In order to verify the correctness of the above design method, this article imports the motion part of the above 3D model into ADAMS software and adds material properties and motion constraints. Marking points are set on the rod *DC*, and the motion trajectory of the double cam five-bar mechanism shown in Fig. 10 below is obtained through the simulation of the software. The simulation data are exported and compared with the theoretical calculation data (shown in Fig. 11), and the error is controlled within 0.2mm, which meets the design requirements. Therefore, the design method proposed in this article is correct and has practical application value.

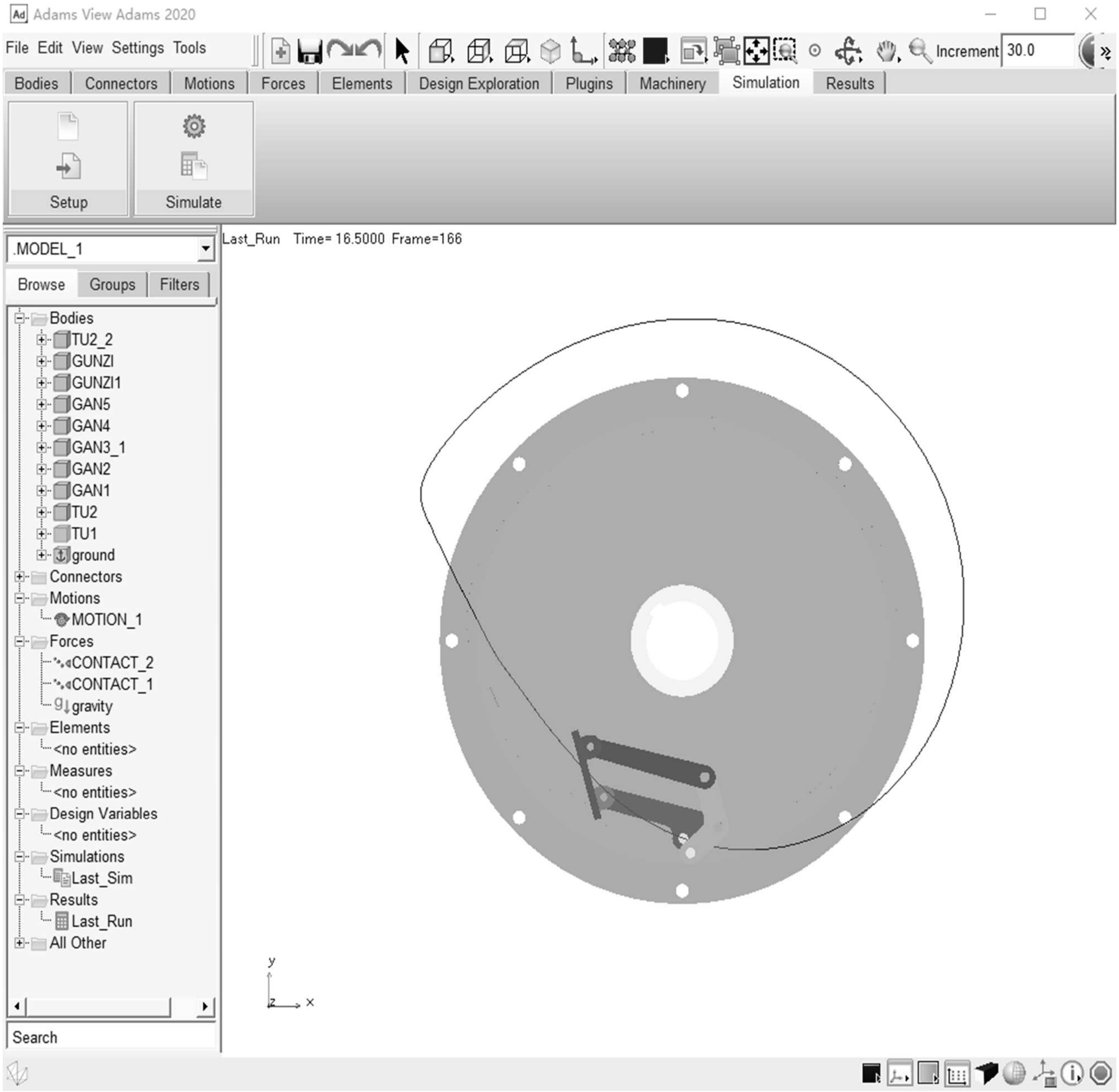

Fig. 10 *Motion trajectory of mechanism*

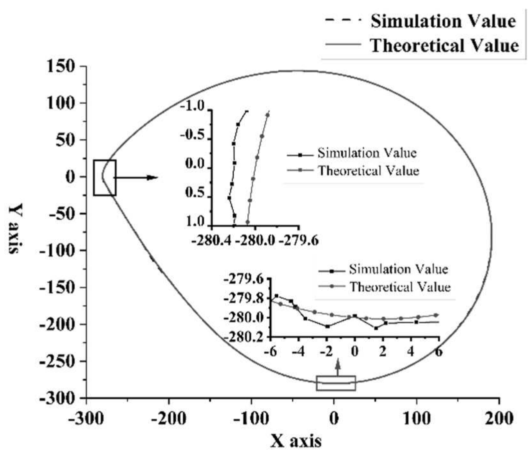

Fig. 11 *Comparison between simulation results and theoretical calculation results*

4 Conclusion

- Based on the analysis of the picking mechanism of the double-cam and five-bar linkage, a design method for the cam and five-bar picking mechanism of the high-speed packaging machine, based on position and orientation constraints, is proposed to better meet the positional and postural requirements during the high-speed pick-up process.
- Using kinematic mapping theory, a mathematical model for the picking mechanism of a double-cam and five-bar linkage system is established. The relationship between the five-bar mechanism and the cam rotation angle under conditions of known posture constraints is determined, and based on this, the profiles of the two cams are established, completing the design of the cam-driven five-bar pick-up mechanism for the packaging machine.
- By taking the design of a cam-driven five-bar mechanism in packaging machines as an example, this article establishes the feasible areas for the curves at hinge points *A* and *B*. By selecting two sets of appropriate mechanism parameters, the design of a double-cam five-bar mechanism for paper picking is completed. This method can achieve the given positions and orientations, and both cams are free from any inner concavity. This design method for the cam-driven five-bar paper picking mechanism of high-speed packaging machines provides a completely new approach for the design of paper picking mechanisms.

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