Motion Control of the Pressing Rollers in the Paper Tape Crimping Machine Based on Servo Control

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Abstract. We analyzed the motion process of the swing roller in the press crimping device and regarded it as the follower of the cam mechanism. We defined the rotation angle of the swing roller equivalent to the stroke of the follower and constructed the electronic cam curve. The control of the swing roller can be realized based on the electronic cam control mechanism. The definition of the electronic cam curve and the angle relationship between the two pressing rollers in the acceleration area were discussed in detail. It is concluded that the rotation angle of the driving shaft is twice as much as that of the swing roller in the acceleration and deceleration area. Based on this finding, the parameters setting of the electronic cam were discussed, which can be set off-line at different speeds of paper tape. Finally, the design idea of the PLC program to realize the above control was discussed and applied to the actual system. The reliability, control precision and stability of the device have obtained the desired effect.

1. Introduction
A flexible bar is made from a loose wire bundle wrapped in paper tape. The outer wrapped paper is rolled into a tray. When the old paper tape is used up, it is necessary to complete the work of paper tape crimping without shutting down the whole production system so as to ensure the continuity of the conveyor paper. The structure of press crimping device is shown in Figure 1. The lead paper on the new paper plate passes through the press crimping area until it reaches the bottom of the paper collecting roller. The old and new paper tape is close to the press crimping area. There is a full circle pressing roller, also known as the light roller and a swing roller in the press crimping area. When the press crimping is needed, the light roller is started first. Then the swing roller is started suddenly. In the pressing process of two pressing rollers, the tape is pressed together.
1) old paper tape  2) new paper tape  3) light roller  4) swing roller  5) waste collecting roller  
6) paper collecting roller  7) new paper plate  8) old paper plate

**Figure 1.** System structure diagram of the press crimping device

Obviously, when the paper tape is pressed, the surface linear velocity of the two pressing rollers must be synchronized with the speed of the paper tape. The light roller can rotate to reach the corresponding speed before pressing. However, the swing roller must complete the process of starting acceleration, accelerating to the corresponding speed, maintaining the speed to complete the work of pressing paper tape, then slowing down and decelerating to stop within a certain angle of rotation. The control of the swing roller and the stroke control of the cam are quite similar. So it can be realized by electronic cam technology based on servo drive.

### 2. Cam and Electronic Cam

#### 2.1. Cam and Cam Curve

Cam mechanism is composed of driving shaft cam, follower and rack. Before the appearance of the digital servo control system, the traditional mechanical cam is the only mechanism that can realize any motion. According to the motion law of the follower, the curve of displacement, speed and acceleration changing with time or cam angle is called cam curve [1]. The most commonly used cam curve is the relation curve between the displacement of the follower and the cam rotation angle. The variation range of the cam angle is generally $0 \sim 360^\circ$.

#### 2.2. Electronic Cam and Electronic Cam Curve

The emergence of servo motor makes the control of complex motions easier to realize. The cam curve of the mechanical cam is applied to the servo motor, which makes the servo motor perform the same action as the cam curve, thus it forms the electronic cam. It requires setting up a virtual driving shaft that is equivalent to a driving shaft cam of a cam mechanism. The mechanical part driven by a servo motor is equivalent to the follower of a cam mechanism [2]. The motor is called the driven shaft. The cam curve that drives the driven shaft is the electronic cam curve. The mechanical cam depends on the mechanical contact between the driving shaft and the follower, so the follower can only travel in a straight line. It's similar to the mechanical cam curve. The electronic cam curve is designed according to the motion relationship between the driving shaft and driven shaft. However, the electronic cam has broken the limitation of mechanical contact, and the follower does not necessarily only complete linear motion and straight stroke. The motion range of driving shaft is also different from $0 \sim 360^\circ$. As
long as there is a movement relationship between the driving shaft and the driven shaft, the electronic cam curve can be constructed [3].

2.3. Definition of the Electronic Cam Curve of the Rotation Angle of Swing Roller
There is a relationship between the rotation angle of the swing roller and the virtual driving shaft, which is consistent with the characteristics of cam mechanism movement. So it's essentially an electronic cam curve. For this purpose, the electronic cam curve of rotation angle of the swing roller is defined. The motion period of swing roller is an electronic cam cycle, which includes the acceleration area, the synchronization area and the deceleration area. The entire process is shown in Figure 2. They can be defined as the relation curves between the rotation angle and speed of the swing roller and the virtual driving shaft. These are the electronic cam curves of the swing roller [4][5].

![Figure 2. The motion process diagram of the swing roller](image)

2.4. Acquisition of the Electronic Cam Curve
Because the speed of the swing roller has experienced the process of accelerating, constant speed and decelerating. In order to ensure the normal transmission of paper tape, the speed curves in the acceleration area and the deceleration area are the cosine curves. The cosine form of speed curve is smooth transition at the corner. The acceleration is zero at the starting point, end point and turning point of the velocity curve. Thereby it avoids the impact force of pulling the paper tape.

The rotation angle of the virtual driving shaft is set to $\delta$, and the corresponding arc length is $Y$, then:

$$Y = \delta \times \frac{\pi}{180} \times R \quad (1)$$

In the formula, R is the radius of the virtual driving shaft, and the current value is the same as that of the swing roller. Because the driving shaft is constant rotation, the time required is $t = \frac{Y}{v}$, and the expression is:

$$t = \frac{1}{v} \times \delta \times \frac{\pi}{180} \times R \quad (2)$$

The velocity curve of the swing roller in the acceleration area is:

$$V_1 = -\frac{v}{2} \cos k_1 t + \frac{v}{2} \quad (0 \leq t \leq t_1) \quad (3)$$

The time spent in the acceleration process is $t_1$, and the angle of rotation is $\beta_1$, and the arc length
corresponding to the rotation angle of the swing roller is:

\[ X_i = \int_0^t V_i dt = -\frac{V}{2k_i} \sin k_i t_i + \frac{V}{2} t_i \]  \( (4) \)

Because the acceleration area of the swing roller is the half cycle of the cosine curve, that is, \( k_i t_i = \pi \), then \( X_i = \frac{V}{2} t_i \), namely \( t_i = \frac{2}{V} X_i \). On the other hand, corresponding to the angle of the swing roller, the corresponding arc length is \( X_i = \beta_i \times \frac{\pi}{180'} \times R \), then \( t_i = \frac{2}{V} \times \beta_i \times \frac{\pi}{180'} \times R \), thus:

\[ \frac{2}{V} \times \beta_i \times \frac{\pi}{180'} \times R = \frac{1}{V} \times \delta_i \times \frac{\pi}{180'} \times R \]  \( (5) \)

Therefore \( \delta_i = 2\beta_i \), which means that the rotation angle of the driving shaft is twice the angle of the swing roller in the acceleration area. In the same discussion on the synchronous area and deceleration area, the electronic cam curve can be obtained as shown in Figure 3.

![Curve diagram of the relationship between the velocity of the swing roller and the angle of the driving shaft](image1)

![Curve diagram of the relationship between the rotation angle of the swing roller and the driving shaft](image2)

**Figure 3.** Curve diagram of running velocity and angle of the swing roller.
In contrast to Figure 2, as shown in Figure 3, when the center line of the swing roller accelerates from the starting position $0^\circ$ to $\beta$, the leading edge of the roller can reach the speed of the paper tape, and the driving shaft turns to $2\beta$. Then the swing roller completes the synchronous constant speed motion, which runs to $\beta_2$. The driving shaft turns to $\beta_2 + \beta_1$. Finally, the swing roller completes the rapid braking process. When the driving shaft rotates to $2\beta - \beta_2 + \beta_1$, the swing roller slows down and stops to the reference point. Thus, the rotation angle of the swing roller and the driving shaft is independent of the speed of the paper tape in the process of implementing the electronic cam curve. The setting of the parameters of the electronic cam curve can be set independently offline. The tracking of the running speed of the paper roller depends entirely on the rotational speed of the virtual driving shaft.

2.5. Actual Electronic Cam Curve of the Swing Roller

The actual structure of the swing roller used in the paper tape crimping device is shown in Figure 4. It can be seen that the radius of the swing roller is 60mm. According to the figure, it can be calculated that the crimping angle of the swing roller is about $60.3^\circ$.

![Figure 4. Structure diagram of swing roller](image)

It is considered that the center line of the swing roller is $0^\circ$ when it is perpendicular to the ground. After the completion of the pressing work, it stops at $90^\circ$, which is the reference point. When the speed of the light roller is consistent with that of the paper tape, the swing roller rotates 90 degrees clockwise from the reference point to $0^\circ$. It starts to start accelerating and the acceleration area is from $0^\circ$ to the front of the swing roller reaches $180^\circ$. Its corresponding rotation angle is $\beta_1 = 270^\circ - 60.3^\circ + 2 = 239.85^\circ$. Then it completes the press crimping work in the synchronous area. The synchronous end position is that the trailing edge of the swing roller reaches $180^\circ$. At this point, the center line of the swing roller is in position of $\beta_3 = 270^\circ + 60.3^\circ + 2 = 300.15^\circ$. After the pressing is completed, it quickly decelerates and rotates $149.85^\circ$. Finally it stops at the reference point and waits for the next working cycle. So the total stroke of the swing roller is $\beta_3 = 300.15^\circ + 149.85^\circ = 450^\circ$.

According to the rotation of the swing roller to the angles $\beta_1$, $\beta_2$, $\beta_3$, the corresponding rotation angles $\delta_1$, $\delta_2$, $\delta_3$ of the driving shaft can be obtained respectively.

\[
\delta_1 = 2\beta_1 = 2 \times 239.85^\circ = 479.7^\circ
\]

\[
\delta_2 = \beta_1 + \beta_3 = 300.15^\circ + 239.85^\circ = 540^\circ
\]

\[
\delta_3 = 2\beta_3 - \beta_2 + \beta_3 = 2 \times 450^\circ - 300.15^\circ + 239.85^\circ = 839.7^\circ \approx 840^\circ
\]

According to the above discussion, the electronic cam curve of the actual swing roller is shown in
3. Realization of the Control System of the Pressing Device

According to the functional requirements of the paper tape pressing device, the control system mainly includes Mitsubishi iQ-F FX5U series PLC, FX5-80SSC-S 8-axis motion control positioning module connected with PLC and servo control system. The concrete structure frame is shown in Figure 6.

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(a) Curve diagram of the relationship between the velocity of the swing roller and the angle of the driving shaft

(b) Curve diagram of the relationship between the rotation angle of the swing roller and the driving shaft

Figure 5. Curve diagram of running velocity and angle of the swing roller

Figure 6. Structure block diagram of the press crimping device control system
The 8-axis motion control positioning module is connected with five servo amplifiers through the optical fiber motion control high-speed bus to realize the interaction of control information [6]. Servo motors as the actuator realize high speed crimping of new and old paper tape.

3.1. Control Realization of the Electronic Cam Curve of Swing Roller

The related software is used to set the related parameters and design the electronic cam curve. The abscissa of the electronic cam curve is a cycle length of the cam, which represents the angle of the driving shaft running in one cycle. The ordinate is the stroke of the cam, which represents the percentage of the rotation angle of the swing roller to total angle. The main parameters of the swing roller are set as shown in Table 1.

### Table 1. Main parameters setting of electronic cam

| Bullet | Name                      | Set-point            |
|--------|---------------------------|----------------------|
| Pr.1   | Unit setting              | 0:mm                 |
| Pr.2   | Per rotation pulse number | 131072Pulse          |
| Pr.3   | Momentum per transfer     | 376800.0um           |
| Pr.4   | Unit ratio                | 1*1 times            |
| Pr.438 | Unit setting selection    | 0:Use the unit of the main input axis |
| Pr.439 | One cycle length of camshaft | 879.646mm          |
| Pr.441 | Cam stroke               | 471000um             |

The cycle length of the camshaft in Table 1 shows that the driving shaft rotates $840^\circ$ in one cycle, and the corresponding arc length is $Y = 840^\circ \times \left(\frac{\pi}{180^\circ}\right) \times 60 = 879.646mm$. The stroke of the cam indicates that the swing roller rotates $450^\circ$ in one cycle, and the corresponding arc length is $X = 450^\circ \times \left(\frac{\pi}{180^\circ}\right) \times 60 = 471000 \text{ um}$. According to the motion law of the swing roller, the relevant data and the parameters of the swing roller electronic cam curve are calculated and set. The design of the electronic cam curve is shown in Figure 7. The percentage of the rotation angles or rotation angles of the swing roller and the driving shaft in the acceleration area, deceleration area, synchronous region are filled in the corresponding intervals. The first interval starts from 0 to 479.755, and the stroke is 53.3%. The second interval starts from 479.755 to the end point of 540.1, and the stroke is 66.7%. The third interval starts from 540.1 to the end point of 840, and the stroke is 100%.

![Figure 7. Electronic cam curve of the swing roller](image)
It can be seen from the figure that the velocity curve is smooth transition at the turning point. The acceleration is not mutated at the starting point, end point and turning point of the velocity curve.

4. Design of the Control Program for the Press Crimping Device

In the whole control system, the paper tape speed of the device is collected by the rotary encoder and sent to the motion control module. The key parameters of the electronic cam have been assigned to the data register of the electronic cam parameters in advance. After the program starts the electronic cam function, the motion control module sends the operation of the electronic cam curve to the servo amplifier to drive the servo motor. The servo motor operates in accordance with the electronic cam curve to complete the pressing work of the paper tape [7]. The flow chart of the crimp control program is shown in Figure 8.

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Figure 8. Flow chart of crimp control program
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5. Conclusion

The swing roller in the crimping device is regarded as a follower of the cam mechanism, the definition of its rotation angle is equivalent to the stroke of the follower. The action electronic cam curve of the swing roller is constructed. Thus, the control of the swing roller can be realized based on the electronic cam control mechanism. The motion angle and speed curve of the swing roller are discussed and the electronic cam curve is designed and implemented in the actual system. The control program is designed, and good control effect is obtained through the experiment, which can be applied in the actual production equipment.

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7. References

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