DESIGN OF HIGH-SPEED WINDING MACHINE FOR THREE-POSITION VARIABLE ANGULAR VELOCITY LITHIUM BATTERY

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The low production efficiency of batteries hinders the development of lithium batteries. In order to obtain the constant linear velocity of the square lithium battery electrodes winding, the geometric model of the rhombic needle and its motion analysis are given. The two-stage tensioner that can cooperate with the winding mechanism is designed to realize the high-speed winding constant tension of the battery cell and ensure the uniform tension between the layers of the cell electrodes. Experiments show the angular velocity of the rhombic needle optimization algorithm can effectively reduce its peak velocity and smooth the angular velocity change.

Keywords: lithium battery; three-position; high-speed winding; variable angular velocity; constant tension

1. Introduction

Lithium batteries are widely used in the market. They become ideal mobile energy storage components because of their large energy ratio, no memory, many charging cycles, light weight and high energy storage safety.

Wu Pingzhong [1] of the Institute of Resources and Environmental Policy of the Development Research Center of the State Council emphasizes that the application of power lithium batteries in the field of electric vehicles can not only replace oil with electricity and reduce greenhouse gas emissions, but also store off-peak electricity; Zhou Fang [2] believes that the large-scale application and technology accumulation of power battery technology in new energy vehicles lay a solid foundation for the development of lithium batteries in the field of energy storage, and the lithium battery industry also creates new economic growth points; Liu Xingjiang [3] speaks out that China has become The world's largest producer and consumer of lithium batteries; Yang Zhenyu [4] points out that the global lithium battery production capacity has increased significantly in recent years and many domestic lithium battery enterprises have surged, thus the lithium battery production equipment is facing technological breakthroughs at present; Dong Fengming [5] believes that the lithium battery market is unprecedented according

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to his analysis of China's lithium battery equipment industry and the demand for lithium battery will further increase. The researches of improving lithium battery performance and production process made by scholars both at home and abroad help widen its application, and the United States already applies it to the aviation field[6-9].The application of lithium batteries in new energy vehicles has gradually entered the electric vehicle market and developed rapidly[10-11].

Under this background, many industry personnel launch researches on lithium battery technology. Some foreign scholars study the lithium battery electrode processing technology. They put forward the improvement process and completed the design of the related system; Stefan Schindler and Michael A. Danzer analyze the influence of cell design on impedance characteristics of cylindrical lithium-ion cells [12]. Muhammad Aydemir [13]and others make a research on increasing productivity in assembling z-folded composites for lithium-ion batteries.

In view of this, this paper proposes a new design of high-speed winding machine for lithium battery with three-position variable angular velocity. Through the analysis of its working principle, the selection principle of needle winding structure and the characteristics of geometric model, this paper studies the motion characteristics of needle to ensure the uniformity, alignment accuracy and cleanliness of cell winding layers. Based on this, the overall layout, three-position winding mechanism, other mechanisms, electronic control system, visual operation interface and automation control are designed.

2. Operational Principle of the High- Speed Winding Machine

The winding machine mainly consists of needle winding mechanism, unwinding and rectifying mechanism, tension mechanism, dust removal mechanism, buffer mechanism, driving mechanism, process rectifying mechanism, clamping and feeding mechanism, diaphragm cutting and wrapping winding and pressing mechanism, entrance clamping mechanism, three-position winding mechanism, gluing mechanism, blanking mechanism and other mechanical modules and software systems. The overall layout is shown in Fig. 1.

The winding machine forms the closed-loop control by active unwinding and rectifying mechanism, driving mechanism, tension mechanism and winding mechanism. Based on the tension mechanism, the approximate constant linear speed of the polar plate is realized to ensure the target fluctuation range of tension.

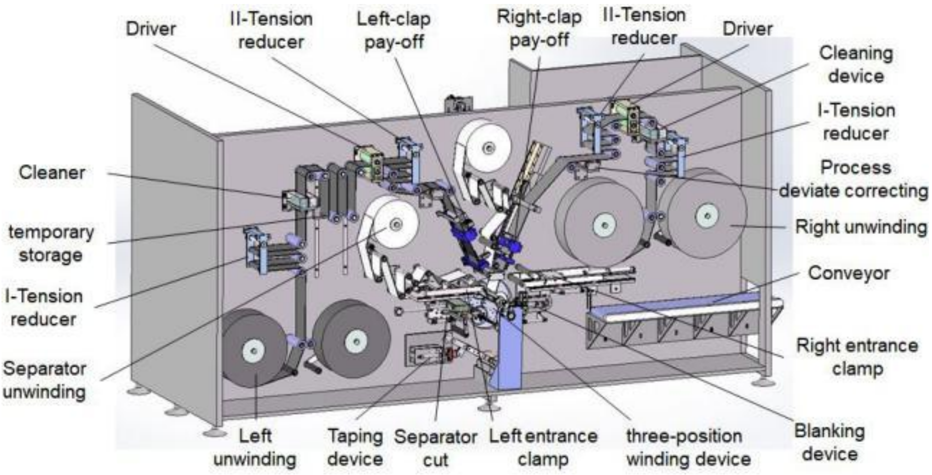


Fig. 1. The winding machine

The unwinding mechanism takes the initiative to unwind during working, after the first-level tension mechanism, dust is removed, and then the driving mechanism drives the electrodes movement; after passing the second-level tension mechanism and the correction process, the electrodes are fed into the three-position winding mechanism by the clamping feeding mechanism, which completes the initial winding of the cell, the wrapping of the cell and the pasting of the anti-loose tape and the blanking respectively. After finishing the winding, the cell is conveyed from the conveyor belt to the subsequent work station, and the process is shown in Fig. 2.

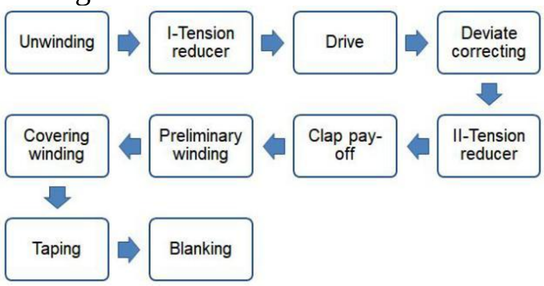


Fig. 2. The manufacturing process of the winding machine

3. Geometric Model and Motion Analysis of the Rhombus Needle

3.1 Geometric Model of the Rhombus Needle

The winding mechanism is the core of the winding machine, and the needle plays a decisive role in the performance of the winding mechanism. The existing winding machine uses thick needle with circumference of about 200 mm and winding speed of 600-800 mm/s. To achieve the target speed of 1000-1500 mm/s, the structure, geometric model and motion characteristics of the needle are supposed to be studied.

The needle mechanism is the core component of the three-position winding mechanism. The electrodes and diaphragms are wrapped around the surface of the needle to form a certain shape of the cell. The needle structure of this design is shown in Fig. 3.

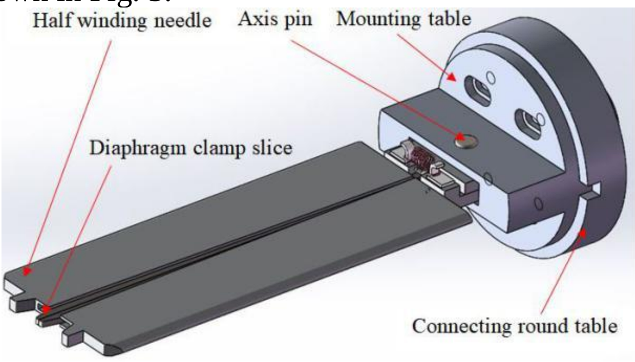


Fig. 3. The needle structure

The shape of the needle can be round, elliptical, rhombic and many other types, among which the rhombic needle winding of rectangular lithium battery batteries has smaller deformation and better uniformity in compression forming. Therefore, this paper chooses rhombic needle to build needle winding mechanism.

The angular velocity of the needle should match the linear velocity of the electrodes when the cell is winding, otherwise, the uniformity between layers of the cell will not reach the standard or the electrodes will be broken. At present, many devices adopt self-learning method to control the constant linear speed of the electrodes, but this kind of method is inefficient. The selection of angle and length information fluctuates greatly, and the control accuracy is low. Besides, different types of needles need to be re-learned.

3.2 The Motion Analysis of the Needle

Based on the selected rhombus needle structure, its model is established as shown in Fig. 4.

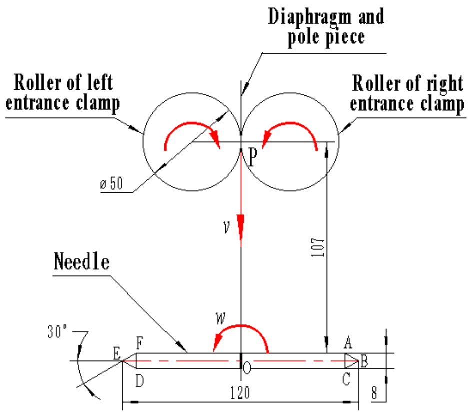


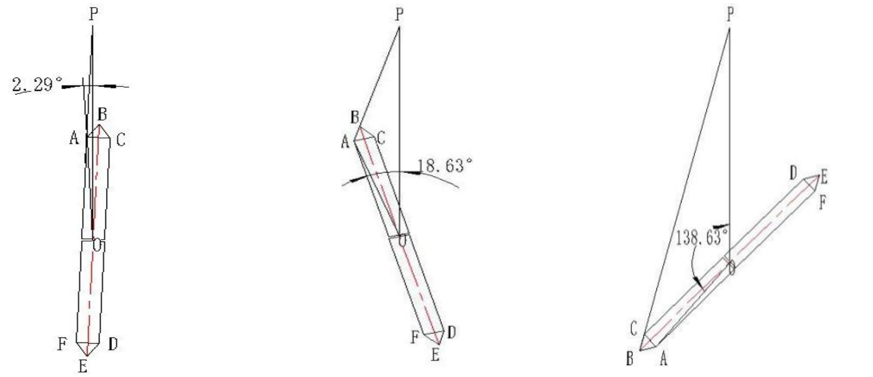
Fig. 4. The winding model of rhombus needle

The diaphragm electrodes are clamped by a needle after passing through the roller. The needle drives the diaphragm electrodes to be wound. The moving speed of the diaphragm electrodes is the same as the linear speed at the contact position of the rhombus needle.

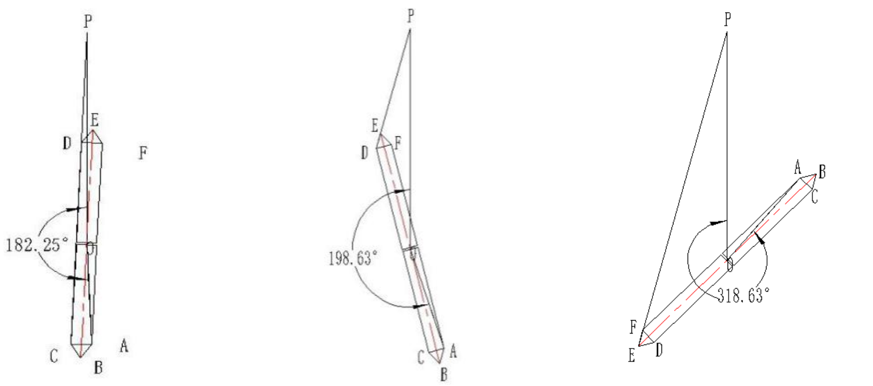
The rhombic needle is composed of six sidelines of AB, BC, CD, DE, EF and FA. The O-point is the center of the needle. The P-point is the tangent point between the electrodes and the roller of left/right entrance clamp. When the P-point of the needle is in line with the six sidelines of the rhombus in turn during the winding process, the needle will appear six limit positions, as shown in Fig. 5.

The length of the *L* electrodes varies with the motion of the needle. It can be expressed as a function *L*=*L*(t) of time *t*. The expression is different at different critical positions, so it is a piecewise function.

This paper takes the first limit position as an example to analyze the relationship between the linear velocity of the electrodes and the angular velocity of the needle. AP is the length of the electrodes, and OA and OP are only related to the geometry of the needle and they are constant.



a.Limit Position 1 b.Limit Position 2 c.Limit Position 3



d.Limit Position4 e.Limit Position5 f.Limit Position 6

Fig. 5. Limit positions of the needle model

The relationship between the linear velocity of the electrodes and the angular velocity of the needle can be obtained as

$$v = \frac{\mathrm{dAP}}{\mathrm{d}t} = \frac{\omega l r_1 \sin\theta}{\sqrt{l^2 + r_1^2 - 2 l r_1 \cos\theta}} \tag{1}$$

Where, l is the distance from the tangent point that between the electrodes and the roller of the entrance clamp to the center of the needle ,$l=\overline{OP}$; ω is the rotate speed of the needle as shown in Fig.4. r_1 is the distance from the outer edge of roller to the center of the needle, $r_1=\overline{OA}$.

By analyzing the six limit positions separately, the motion state of the needle in one circle can be obtained:

$$\begin{cases} v = \dfrac{\omega l r_1 \sin\theta}{\sqrt{l^2 + r_1^2 - 2 l r_1 \cos\theta}} & \theta \in [\theta_1, \theta_2) \\ v = \dfrac{\omega l r_1 \sin(\theta-\alpha_1)}{\sqrt{l^2 + r_1^2 - 2 l r_1 \cos(\theta-\alpha_1)}} & \theta \in [\theta_2, \theta_3);\ \alpha_1 = \angle AOB \\ v = \dfrac{\omega l r_1 \sin(\theta-\alpha_2)}{\sqrt{l^2 + r_1^2 - 2 l r_1 \cos(\theta-\alpha_2)}} & \theta \in [\theta_3, \theta_4);\ \alpha_2 = \angle AOC \\ v = \dfrac{\omega l r_1 \sin(\theta-\alpha_3)}{\sqrt{l^2 + r_1^2 - 2 l r_1 \cos(\theta-\alpha_3)}} & \theta \in [\theta_4, \theta_5);\ \alpha_3 = \angle COF = \pi \\ v = \dfrac{\omega l r_1 \sin(\theta-\alpha_4)}{\sqrt{l^2 + r_1^2 - 2 l r_1 \cos(\theta-\alpha_4)}} & \theta \in [\theta_5, \theta_6);\ \alpha_4 = \angle AOE = \pi + \angle DOE \\ v = \dfrac{\omega l r_1 \sin(\theta-\alpha_5)}{\sqrt{l^2 + r_1^2 - 2 l r_1 \cos(\theta-\alpha_5)}} & \theta \in [\theta_6, \theta_1);\ \alpha_5 = \angle AOF = \pi + \angle DOF \end{cases} \tag{2}$$

Where, θ_1 is the angle between the center of the needle and the outer point and the vertical line， $\theta_1=\angle AOP$;θ_2 is the angle between needle radius and vertical line， $\theta_2=\angle BOP$. θ_3 is the angle between the line from the center of the roll pin to the inner edge point and the vertical line， $\theta_3=\angle COP$.θ_4 is the angle between the line from the center of the roll pin to the symmetrical point of point a and the vertical line， $\theta_4=\angle DOP$;θ_5 is the angle between the symmetrical point of point B and the vertical line， $\theta_5=\angle EOP$.θ_6 is the angle between the symmetrical point of point C on the inner edge of the needle and the center line and the vertical line of the needle $\theta_6=\angle FOP$.

Form the Eq. (2), the relationship between the angular velocity and the linear velocity of the electrodes is obtained as follows:

$$
\begin{cases}
\omega = \dfrac{v\sqrt{l^2 + r_1^2 - 2lr_1\cos\theta}}{lr_1\sin\theta} & \theta \in [\theta_1, \ \theta_2) \\
\omega = \dfrac{v\sqrt{l^2 + r_1^2 - 2lr_1\cos(\theta-\alpha_1)}}{lr_1\sin(\theta-\alpha_1)} & \theta \in [\theta_2, \ \theta_3) \ ; \alpha_1 = \angle AOB \\
\omega = \dfrac{v\sqrt{l^2 + r_1^2 - 2lr_1\cos(\theta-\alpha_2)}}{lr_1\sin(\theta-\alpha_2)} & \theta \in [\theta_3, \ \theta_4) \ ; \alpha_2 = \angle AOC \\
\omega = \dfrac{v\sqrt{l^2 + r_1^2 - 2lr_1\cos(\theta-\alpha_3)}}{lr_1\sin(\theta-\alpha_3)} & \theta \in [\theta_4, \ \theta_5) \ ; \alpha_3 = \angle COF = \pi \\
\omega = \dfrac{v\sqrt{l^2 + r_1^2 - 2lr_1\cos(\theta-\alpha_4)}}{lr_1\sin(\theta-\alpha_4)} & \theta \in [\theta_5, \ \theta_6) \ ; \alpha_4 = \angle AOE = \pi + \angle DOE \\
\omega = \dfrac{v\sqrt{l^2 + r_1^2 - 2lr_1\cos(\theta-\alpha_5)}}{lr_1\sin(\theta-\alpha_5)} & \theta \in [\theta_6, \ \theta_1) \ ; \alpha_5 = \angle AOF = \pi + \angle DOF
\end{cases}
\tag{3}
$$

It can be seen from Eq. (3) that the speed control of the winding of the square lithium battery is complicated, and each rotation of the needle is divided into six stages, so that the tension control of the winding of the square lithium battery is a difficult point. The winding speed control algorithm is written according to Eq. (4), and with the tension control and the buffer mechanism, the difficulty can be solved.

As can be seen from the geometric model and motion analysis of the square lithium battery, the battery winding process will be beyond the control of the servo system: when the rhombus needle line AF or the line CD coincides with the P-point, the turning radius of the needle is half of the thickness of the needle, which is 4mm. in order to obtain a large electrodes speed (>600mm/s), the angular velocity should reach a large value (>9000r/min), which is far beyond the working range of the servo system, so the auxiliary tension mechanism must be added when the square lithium battery winding machine is working, so that the electrodes maintain uniform interlayer tightness during the winding process.

4. Design of three-position variable angular velocity winding mechanism

The winding of the lithium battery includes three steps of preliminary winding, wrapping winding and anti-loose tape. The conventional winding machine has only one processing position, and the cell winding is completed by a centralized process. This method cannot fully utilize the equipment efficiency, and the processing speed is difficult to increase.

After analysis, it is found that the processing time of initial winding is similar to that of wraping winding, which makes the dispersing process possible. In order to realize super high-speed winding, a three-position winding mechanism is designed, which concentrates the three processes of cell winding on three positions of a turntable to realize simultaneous work of multiple processes.

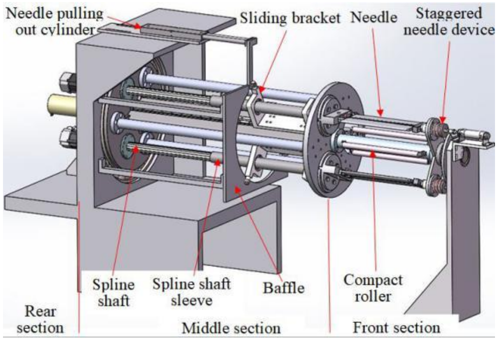


Fig. 6. Three-position winding machine

The whole mechanism can be divided into front, middle and back sections, as shown in Fig. 6. The front section includes supporting mechanism, dislocation needle mechanism and needle mechanism, and the dislocation needle mechanism cooperates with the needle rolling mechanism to clamp the diaphragm; the middle section includes connecting mechanism, needle transmission mechanism and sliding mechanism to complete the rotation, revolution and expansion of the needle.

The back section includes needle rotation drive mechanism, turntable drive mechanism, support and wiring slip ring. The three-coiling needle mechanism is independent of each other and driven by servo motor. The whole three-position coiling table is driven by motor gear. In order to solve the winding problem of the connection of the needle-driven motor during revolution, a 12-channel connection slip ring is adopted, and the back mechanism is shown in Fig. 7.

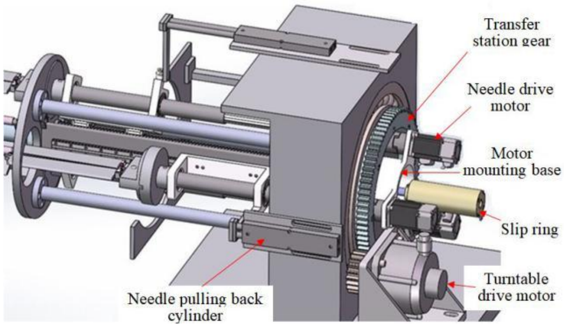


Fig. 7. The back-end drive of three-position winding mechanism

In the front section, three identical winding positions are designed and distributed on the 1200 turntable apart from each other. The three positions rotate alternately counterclockwise to perform position conversion. Each position needle is rotated around its own axis to achieve the cell winding action. Fig. 8. shows the layout and direction of movement of the three positions. The needle is extended at the station 1, and the diaphragm is clamped, and the initial winding is performed; the needle maintains the clamping state in the station 3, and carry out the wrapping winding, and attach the anti-loose tape; the needle is taken out from the battery cell in the station 3 to achieve the blanking.

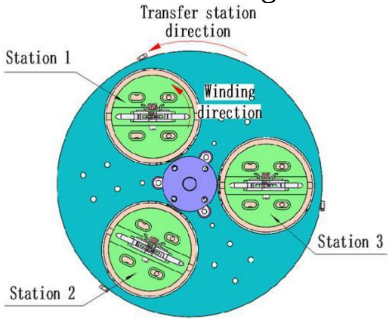


Fig. 8. Position layout

5. The Optimization Test of the Needle Angular Velocity

The optimization of needle angular velocity is to obtain the optimal value of constant linear velocity of electrodes and smooth curve of velocity variation.

Considering the speed compensation of buffering mechanism and winding tension mechanism near the limit position of needle angular velocity, this paper optimizes the angular velocity of driving spindle and obtains the optimal value of needle angular velocity near the limit position in order to realize the smooth change of needle angular velocity.

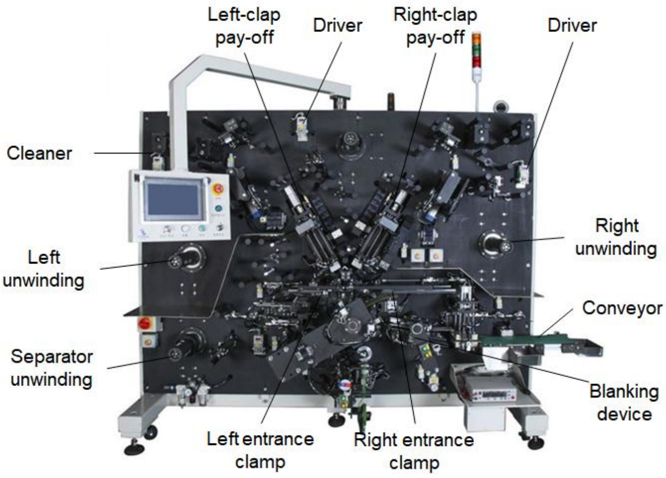


Fig. 9. The experimental winding machine

The experimental winding machine is shown in Fig. 9. The optimum results of needle angular velocity are tested. The experimental machine is in accordance with the design in this paper. On the premise of controlling the constant linear velocity of the electrodes, the velocity-time curves of the needle speed before and after optimization are compared to measure the effect of the optimization algorithm. The angular velocity data of needle is obtained by driving servo motor encoder, the linear velocity of electrodes is calculated by the angular velocity of the driving roller and entrance clamping roller, and the tension force of electrodes is obtained by tension force sensor.

The needles reach the limit position at angles of 178.40and 358.40during the test. After the actual adjustment, the optimization interval is determined to be 1690-1880, 3490-80. The test set the linear velocity of electrodes to 166mm/s. According to the theoretical calculation, the theoretical angular velocity value of the needle is obtained. The speed of the spindle is optimized to obtain the angular velocity optimization value of the needle. The change of needle speed with needle motion is shown in Fig. 10.

It can be seen directly from Fig.10 that there are sharp angles in the angular velocity curve of the needle before optimization, and the sudden change of speed will produce a great impact, and the speed value reaches more than 7500 r/min, so the servo system cannot meet such movement requirements; after optimization, the maximum speed of the needle is reduced to less than 5250 r/min, and the speed curve is smooth.

Then the winding speed measurement test is carried out with using optimization algorithm and without using it during the actual winding process.

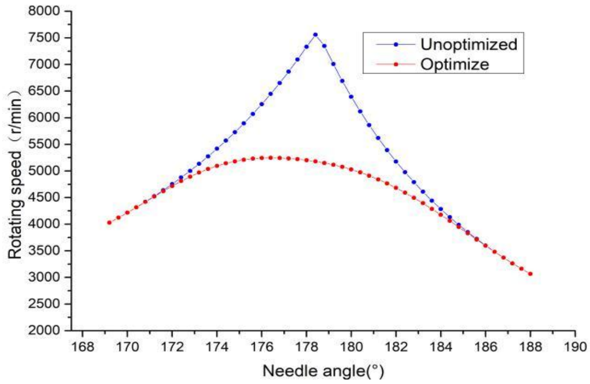


Fig. 10. The needle angular velocity before and after optimization

Fig.11. is a graph showing variation curve of the angular velocity of the needle during the winding process without the optimization; Fig.12 shows the speed-time curve for optimizing the two limit positions.

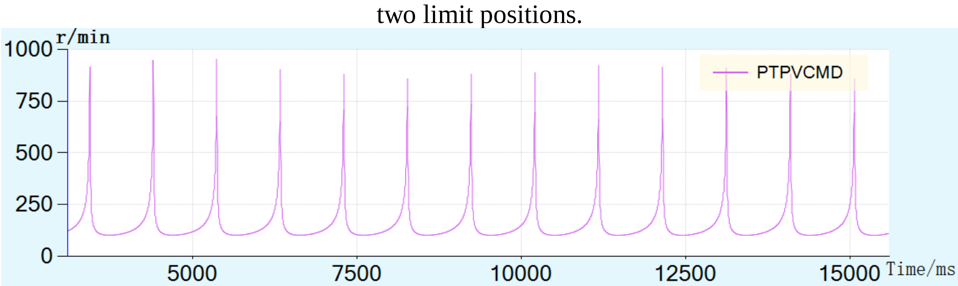


Fig. 11. Speed-Time Curve Without Optimization

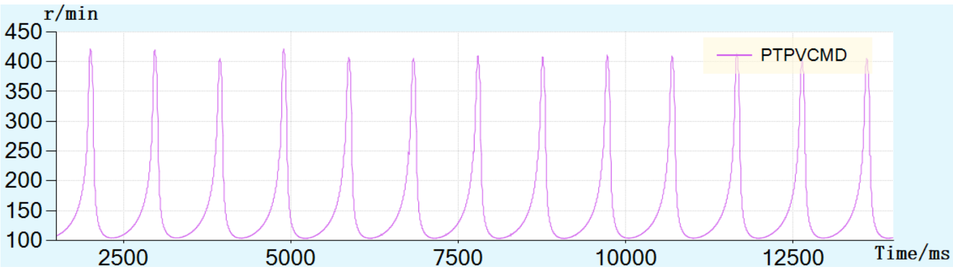


Fig. 12. Optimizing the speed-time curve of two limit positions

Comparing Fig.11. with Fig.12., it can be seen that the unoptimized needle rotation speed has two peaks at 1000 r/min per cycle, which is much quicker than other periods; after optimizing one limit position, the peak angular velocity of the needle is reduced by about 60% after the cycle, and the peak change is moderate. As it can be seen from Fig. 12, after optimizing the two limit positions, the peak angular velocity of the needle is reduced to about 400 r/min, which is 60% lower than the unoptimized peak.

However, due to the limited speed compensation capability of the auxiliary mechanism, the angular velocity optimization of the needle can not be arbitrarily increased, and the greater the degree of optimization, the higher the response speed and stability requirements of the auxiliary system, which also makes the optimization of the needle angular velocity more difficult, so it can only be optimized within a certain range.

The test results show that while ensuring the constant linear velocity of electrodes, the peak angular velocity of the rhombus needle can be significantly reduced by the optimization algorithm, and the speed change is smoother. This makes the winding speed control more stable, reduces the impact of equipment operation and also lowers the difficulty of tension control, and can further improve the quality of the cell.

6. Conclusion

This paper builds the geometric modeling of the rhombus needle, analyzes the relationship between the angular velocity of the needle and the linear velocity of electrodes, and obtains the linear velocity control function of electrodes, which provide algorithm support for constant line speed control. The two-stage tension mechanism cooperates with the unwinding mechanism and the winding mechanism reasonably. A closed-loop control system is formed under the control algorithm to ensure the tension fluctuation range requirement during high-speed winding. It was verified on the actual equipment. The diamond coil needle was 20mm thick and 120mm wide. The winding speed reaches 2000mm/s~2500mm/s within 5%~10% of the tension fluctuation, and the maximum linear speed of the winding needle is less than 3000mm/min, which meets the requirements of the motor's normal motion range.

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