Research on speed regulation method of winding machine based on rectangular line mode

Y S Zhang¹2, H W Ma¹ and H T Wang¹

¹College of Mechanical Engineering, Xi'an University of Science and Technology, Xi'an, 710054, China
E-mail: 714720644@qq.com

Abstract. In the traditional semi-automatic winding machine winding process, the tension of the enameled copper wire changes greatly, and the cable is inaccurate, and cannot be separated from the manual machine. The emergence of automatic winding machine realizes the automation of winding production, reduces the labor intensity of winding, and greatly improves production efficiency. In order to improve the winding quality of the rectangular coil of the motor, a motor winding automatic winding machine is designed. The kinematics and dynamics analysis of the winding process of the winding machine were carried out. The kinematics of the enameled copper wire and the working principle of the governing mechanism were studied. The kinematics mathematical model of the enameled copper wire was simulated. The results show that the designed motor coil automatic winding machine has accurate cable routing and smooth winding process.

1. Introduction
In the manual winding process, the production efficiency of the winding is low due to the variety of the wound products and the proficiency of the operator. Especially in the increase of the number of turns, such as the number of individual motor turns in the millennium or 10,000-degree motor, the manual winding efficiency is even lower [1-3]. Due to the inconsistent tension of the wires, the accuracy of the number of windings is not guaranteed, and raw materials are wasted. The magnitude of the external tension applied to the magnet wire depends on the cross-sectional dimension of the magnet wire. Different specifications of the electromagnetic wire, the tension required in the coil winding process is also different. If the tension is too large, the insulation of the bread outside the electromagnetic wire is easily scratched. If the tension is too small, the coil forming is certainly not ideal [4-7].

The foreign winding industry has developed earlier and is developing rapidly [8-10]. METEOR, Switzerland, mainly produces precision winding machines, including semi-automatic and fully automatic workpiece rotary winding systems. During the winding process, both ends of the workpiece must be clamped, which will cause the magnetic properties of the workpiece to change, affecting the quality of the workpiece [11,12]. Japan's Hitachi Company uses the workpiece as the main body and uses the flying fork to wind the high-speed rotary winding. This not only ensures the quality of the rotating body is constant, but also runs smoothly, avoiding the additional installation torque to deform the workpiece and affect the workpiece quality [13]. In order to meet the needs of the industry, combined with China's national conditions, it is imperative to develop a fully automatic winding machine with excellent performance and low price [14,15]. The traditional motor coil winding
machine working state and winding process are analyzed, and a motor coil automatic winding machine experimental platform with smooth winding process and precise cable routing is designed to achieve automatic winding, reduce human factors and reduce labor intensity to increase production efficiency.

2. Motor coil automatic winding machine structure
The conventional winding machine is mainly composed of a clamping mechanism, a coil, an electric motor, and a wire mold. The working principle is that the motor drives the wire mold to rotate, and the copper wire is wound around the wire mold to obtain the required coil, as shown in figure 1.

![Figure 1. Winding machine schematic.](image1)

In the figure, the motor rotates at a constant speed, but since the motor coil is usually rectangular and has a large volume, the wire mold may vibrate during the winding process, the winding speed is uneven, and the tension is uneven. However, the tensioning device in the figure can not adjust the clamping force at any time, so the performance of the wound coil will be affected to some extent.

The motor coil automatic winding machine system consists of six parts: control system, winding mechanism, cable arranging mechanism, speed regulating mechanism, guiding mechanism and pay-off mechanism. Its winding machine assembly is shown in figure 2.

- **Winding mechanism:** the winding mechanism motor is used as the power source of the whole system, and the driving line mode realizes the rotary motion of the wire mold when winding. The mechanism is composed of DC servo motor, motor bracket, coupling bracket, coupling, and wire mold. The coupling is connected with the wire mold, and the coupling bracket is mounted on the frame to remove the influence of the cantilever beam and ensure the neutrality of the motor output shaft. The wire mold uses a bolt-on clamping plate as a clamp to wind the coil. In order to prevent the coil from rotating without tension during the pay-off, a rotary damper is installed on the pay-off mechanism to adjust the tension of the wire on the lacquered copper wire during the pay-off.

- **Cable arranging mechanism:** The mechanism is composed of a slider, a connecting rod, an internal rail, a motor base, and a stepping motor. The stepping motor rotates at a constant speed, and the crank slider is driven to perform periodic motion. By changing the connecting rod, changing the stroke of the slider, controlling the pulse frequency received by the stepping motor to change the width of the wound coil, the enamelled copper wire passes through the long hole in the slider, and the two deep groove ball bearings are connected in the slider. The sliding friction is converted into rolling friction, thereby achieving a stable and uniform line of the mechanism.

- **Speed regulating mechanism:** The speed regulating mechanism adopts a combined structure of rollers and springs. When the rectangular coil is wound by a spring, the copper wire of the enamelled copper is buffered by the tension change, and the winding speed is adjusted. The utility model solves the problems that the axial length of the coil is increased due to the manual operation and the need for continuous tapping and shaping during the winding
process, and the material for the motor production is reduced, and the weight of the motor is reduced. volume.

- Guide and pay-off mechanism: The guide mechanism is composed of a roller structure, and a frame is shared with the speed-regulating mechanism. The nylon material idler is used to plan the winding path, which reduces the weight of the mechanism and reduces the rolling friction on the paint. Damage to the copper wire insulation layer. As the whole system supply mechanism, the pay-off mechanism is relatively simple in structure, and the reel is fixed by the fixed form of the tailstock. The rotary damper is installed on one side of the frame to provide damping for the rotation of the reel, which solves the problem of inertia rotation of the reel.

3. Principle analysis of speed regulating mechanism of winding machine

The traditional winding machine does not have a constant tension control mechanism, and the tension control is obtained by the worker continuously adjusting the manual control splint. The process cannot rely on the experience of the worker, and the constant tension cannot be achieved, thereby causing the winding coils to be inconsistent and affecting the motor winding. the quality of. In the winding process, since the wire mold is generally rectangular in cross section, the wire moving speed is uneven and the coil tension is not constant. These factors will also cause the electromagnetic wire to be damaged, the coil size is inconsistent, and the winding work is difficult. Therefore, the speed governing mechanism of the winding machine must be able to ensure the stability of the coil winding process.

3.1. Motion analysis without speed regulation

First, we discuss the movement of the enamelled copper wire when the winding machine is not equipped with a speed governing mechanism. Since the wire mold is far away from the wire reel, regardless of the thickened size of the copper wire wound on the wire die during the winding process and the thinned size of the enamelled copper wire on the wire reel, it can be considered that the lacquered copper wire periodically vibrates when the wire is wound in the wire.

Kinematic analysis of the enamelled copper wire was performed during the process of intercepting the rotation of the wire mold. In this process, the enamelled copper wire passes through the four corner points of the wire mold, so the rotation motion of this week can be divided into four segments for analysis.

![Figure 3](image1.png)  
*Figure 3. The first section of the wire mold winding.*

![Figure 4](image2.png)  
*Figure 4. Schematic diagram of the second section of the wire mold winding.*

![Figure 5](image3.png)  
*Figure 5. The third section of the wire mold winding.*

![Figure 6](image4.png)  
*Figure 6. Schematic diagram of the fourth section of the wire mold winding.*
The first paragraph: the wire mold starts to rotate from the starting horizontal position until the enamelled wire passes the first corner point position as shown in figure 3.

The second paragraph: the wire mold continues to rotate after the enamelled copper wire passes through the first corner point until the enamelled copper wire passes through the second corner point as shown in figure 4.

The third paragraph: the wire mold continues to rotate after the enamelled copper wire passes through the second corner point until the enamelled copper wire passes through the third corner point as shown in figure 5.

The fourth paragraph: the wire mold continues to rotate after the enamelled copper wire passes through the third corner point until before passing through the fourth corner point as shown in figure 6.

When the center of the wire mold is larger than the wire spool center from the center of the wire, the angle Q can be ignored. The center of the wire mold and the center of the coil are \( L=2100 \) mm, \( a=200 \) mm, \( b=50 \) mm. Calculate the angle \( W \) to which the line mode is turned when the first and second segments are converted. The solution is \( W1=88 \) degrees and \( W2=91 \) degrees.

The reason for the double solution is to ignore the angle \( Q \). The essence of ignoring the angle \( Q \) is that the enamelled copper wire is always horizontal during the rotation of the wire die. Under the ideal state, the wire die is turned to the angle \( W=90 \) degrees, and the first segment and the second segment are converted, and the obtained result is obtained. Approximate to the ideal state.

The resulting length change \( d_L \) of the four-stage enameled wire is:

The first stage: \( d_L = L - \frac{\sqrt{a^2 + b^2}}{2} \cos \left( W + \arctan \frac{b}{a} \right) \); The second stage: \( d_L = b + L - \frac{\sqrt{a^2 + b^2}}{2} \cos \left( W - \arctan \frac{b}{a} \right) \);

The third stage: \( d_L = b + a + L - \frac{\sqrt{a^2 + b^2}}{2} \cos \left( W - \pi - \arctan \frac{b}{a} \right) \); The fourth stage: \( d_L = b + 2a + L - \frac{\sqrt{a^2 + b^2}}{2} \cos \left( W - \pi - \arctan \frac{b}{a} \right) \).

The trace speed \( v_L \) changes to:

The first stage: \( v_L = \sqrt{a^2 + b^2} \omega \sin \left( W + \arctan \frac{b}{a} \right) \); The second stage: \( v_L = \sqrt{a^2 + b^2} \omega \sin \left( W - \arctan \frac{b}{a} \right) \);

The third stage: \( v_L = \sqrt{a^2 + b^2} \omega \sin \left( W - \pi + \arctan \frac{b}{a} \right) \); The fourth stage: \( v_L = \sqrt{a^2 + b^2} \omega \sin \left( W - \pi - \arctan \frac{b}{a} \right) \).

The line acceleration \( a_L \) changes to:

The first stage: \( a_L = \frac{\sqrt{a^2 + b^2}}{2} \omega^2 \cos \left( W + \arctan \frac{b}{a} \right) \); The second stage: \( a_L = \frac{\sqrt{a^2 + b^2}}{2} \omega^2 \cos \left( W - \arctan \frac{b}{a} \right) \);

The third stage: \( a_L = \frac{\sqrt{a^2 + b^2}}{2} \omega^2 \cos \left( W - \pi + \arctan \frac{b}{a} \right) \); The fourth stage: \( a_L = \frac{\sqrt{a^2 + b^2}}{2} \omega^2 \cos \left( W - \pi - \arctan \frac{b}{a} \right) \).

Figure 7. Enamelled wire length change curve.
Figure 8. Difference curve.
Solving the kinematics equation, the calculation results are shown in figure 7. The red curve in figure 7 is the actual variation curve of the enamelled copper wire length, and the black straight line is the ideal change. From this, the difference curve between the two lines can be obtained, as shown in figure 8. The curve of the line speed is shown in figure 9. The curve of the line acceleration is shown in figure 10. From the above analysis results, the linear velocity, acceleration, and line length change periodically during the one-rotation of the rectangular line. The linear mode is cyclically shifted during the winding, and the tension on the enamelled wire changes greatly.

Figure 9. Enamelled wire trace speed curve.

Figure 10. Enamelled wire trace acceleration curve.

3.2. Motion analysis during speed regulation
The speed regulation process of the spring roller speed regulating mechanism in the space can be roughly divided into four stages: the falling force, the returning equilibrium position, the rising and the returning equilibrium position under the component force of the enamelled copper wire pulling force. Since the roller speed control mechanism uses light materials, the influence of the mechanism gravity on the speed regulation process of the winding machine is reduced. Therefore, the four stages have a symmetrical relationship when moving in the space, and the space is adjusted by the idler mechanism. The periodic reciprocating motion adjusts the wire speed of the enamelled copper wire to improve the quality of the winding machine when winding the rectangular coil.

In the winding process of the winding machine, when the enamelled copper wire is subjected to the spring action in the speed regulating mechanism, the winding working process is as shown in figure 11:

Figure 11. Speed regulation mechanism speed diagram.

Figure 12. Schematic diagram of speed governing mechanism.

At this point, the working diagram of the speed governing mechanism is shown in figure 12.
For comparison, the dimensions in the calculation below are the same as above, L=2100 mm, a=200 mm, b=50 mm, taking d=1000 mm. Set the initial position of the spring, that is, the position when the spring is not deformed. In order to avoid excessive deformation of the spring, the intermediate position of the enamelled wire at the upper and lower limits at the position in the natural
state is taken as the initial position of the spring.

The lower limit position is shown in figure 13, where $c_1$:

$$c_1 = \frac{2}{1} \left[ \frac{2}{1} - \frac{b}{2} \right] - r.$$

The upper limit position is shown in figure 14, where $c_2$:

$$c_2 = \frac{d}{2} \left( \frac{r}{2} - \frac{b}{2} \right)^2 + 1 \frac{a^2 + b^2}{l}.$$

Then the distance $c$ of the center position of the spring from the center line of the line mold is:

$$c = \frac{c_1 + c_2}{2}.$$

A similar method to that without the speed governing mechanism is used to model the length, trace speed and acceleration of the enameled wire during the one-turn rotation of the rectangular wire mold. The simulation results are shown in figure 15.

The red curve in the figure is the actual curve of the length of the enameled copper wire, the black line is the ideal curve, and the blue curve is the curve of the length of the enameled copper wire without the speed governing mechanism. It can be seen that after increasing the speed governing mechanism, the length change of the enameled copper wire is very close to the ideal curve. From this, the difference curve of the two lines can be obtained, as shown in figure 16. The difference is very small and can be ignored.

Figure 13. Lower limit position.  
Figure 14. Upper limit position.

Figure 15. Increase the speed change diagram of the speed governing mechanism.  
Figure 16. Line length difference curve.

Figure 17 shows the curve of the trace speed of the enameled copper wire. The blue curve shows the curve of the wire speed of the enameled copper wire without the speed governing mechanism. It can be seen that after increasing the speed governing mechanism, the wire speed of the enameled copper wire is close to a constant speed. The curve of the line acceleration is shown in figure 18. It can
be seen that the line is approximately zero, and the uniform circular motion of the line mode is realized.

![Figure 17. Trace speed curve.](image)

![Figure 18. Trace acceleration change.](image)

From the above results, it can be seen that after the speed governing mechanism designed in this paper is added to the winding machine, the tension change caused by the periodic vibration during winding is buffered by the spring roller speed regulating mechanism, thereby achieving the speed of the enamelled copper wire. The purpose of the adjustment is to change the periodic shifting circular motion to a nearly uniform circular motion, thereby improving the winding work process.

4. Conclusion
The motor coil is the core of the motor. The quality of the motor coil directly affects the quality and performance of the motor product. The winding of the motor coil is not tight, and the short-circuit resistance of the motor will be reduced, which directly affects the quality of the motor. Aiming at the coil speed regulation problem of the motor coil automatic winding machine, the kinematics equation of the enamelled copper wire in the winding process is established. The simulation calculation results show that the speed change mechanism changes the line length variation of the copper wire through the displacement change in the space. The value curve is compensated, and the purpose of adjusting the copper wire routing speed is achieved. The periodic shifting circular motion of the copper wire is changed to a uniform uniform circular motion, which indicates that the designed speed governing mechanism can meet the requirements of the smoothness of the winding process. The analysis method can be applied to windings of different specifications, so that the winding machine has a certain flexibility and widens the production range of the product.

References
[1] Zhu Q P 2005 Development of automatic winding machine for transformer high voltage coil China Science and Technology Information 2005 5-6
[2] Mao J X, Liu W and Zhou G F 2012 Study on control method of automatic winding machine with high precision Computer Measurement & Control 20 95-7
[3] Zhang J H 2013 Development of 10 kV large-scale wound three-phase asynchronous motor Electrical Manufacturing 2013 47-9
[4] Shen J X and Fan Z X 2008 Development trend and key technologies of modern electric machines Small & Special Electrical Machines 36 55-7
[5] Wen J B, Wang G H and Wang C J 2011 Numerical calculation of medium-sized high-voltage induction motor rotor temperature fields based on coupled field Explosion-Proof Electric Machine 46 1-3
[6] Zhang Q, Chen C J and Yan Y Z 2007 NC system based on motion controller for deflection winding machine Machinery Design & Manufacture 2007 162-4
[7] Ma Z L and Gao X M 2004 Design of dedicated flat winding machine Machine Tool & Hydraulics 2004 120-1
[8] Xie L F, You L R and Wang L S 2009 Design of hybrid controller base on PC104 and PLC for automatic winding-machine Modular Machine Tool & Automatic Manufacturing Technique 2009 10-6
[9] Wei H B, Zhu Y H and Zheng H H 2005 Design of JR-28 automatic winding machine for metallized film capacitors Electronics Process Technology 2005 1-3
[10] Barcaro M, Bianchi N and Magnussen F 2011 Six-phase supply feasibility using a pm fractional-slot dual winding machine IEEE T. Ind. Appl. 47 2042-50
[11] Li H 2011 Research on vision-based error detection system for optic fiber winding Int Conf Optical Instruments and Technology: Optoelectronic Imaging and Processing Technology (Beijing, China) pp 40-1
[12] Djurović S, Vilchis-Rodriguez D and Smith A C 2012 Vibration monitoring for wound rotor induction machine winding fault detection Xxth International Conference on Electrical Machines (Marseille, France) pp 1906-1912
[13] Sauter D, Jamouli H, Keller J Y et al 2005 Actuator fault compensation for a winding machine Control Eng. Pract. 13 1307-14
[14] Yuan X L, Tian H, Duan N et al Development of low-speed CNC winding machines Sci. Technol. Innov. 2014 7-8
[15] Li X F 2017 Improvement of synchronization control accuracy of automatic cable winding machine Electronic Technology & Software Engineering 2017 116-7