Research on the Control System of Winding Tension of Strip Stator

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Abstract. In order to solve the problem of severe tension fluctuation in the winding process of strip stator, a tension control system is built with Micro-Controller Unit as controller, encoder as sensor and servo motor as actuator. Besides the employment of traditional PID feedback control, a feed-forward control link is introduced at the same time. The simulation results of PID control with and without feed-forward are compared. In addition, experiments under different working conditions are also carried out. Specifically, when the desired tension value is set at 500g along the 0.35mm enameled wire that being wound onto a strip stator at 900r/min, the tension overshoot and swing angle fluctuation are 0.88° and ±0.53° respectively. It is also found that, rather than the speed of the frame, it is the tension that significantly effects the control performance in the proposed system.

1. Introduction

The stator is an important part of the motor. A common way to fabricate a motor stator is to initially wind enameled wires onto separate strip stators and assemble them together afterwards to form a whole circle. In the process of winding a strip stator, enameled wires are likely to lose the tension and over-stacked if the tension is too small along wires. Contrarily, overload tension will induce either the unevenness on surface of products or the snap of wires[1]. Therefore, the tension of enameled wire must be well controlled in the winding process of the strip stators of the motor.

Song et al. systematically studied the tension control of circular coil winding and presented a improved PID tension control method[2]. Xue studied the causes of tension and adopted PID control method to control enameled wire tension[1]. Lu et al. studied the active tension control, in which the estimated linear velocity was used to reduce the hysteresis[3]. Wang et al. modeled and analyzed the winding process of the i-wheel winding machine, and presented the physical model of the winding process[4]. Hu et al. studied the tension fluctuation problem in the winding process of different coils and designed a tension control device[5]. Hao et al. proposed a new online linearized iteration scheme, which used model predictive control to control rope tension[6]. Qiang et al. established a mathematical model of the control system and a transfer function simulation model for the wire tension control of high-speed wire cutting, and used PID method to control the tension[7]. Leif et al. optimized the winding parts and production process to improve the performance of the winding machine[8]. Pan et al. optimized the controller and actuator based on the model, which can achieve higher speed winding[9].

Based on the reviews above, PID control method can be applied to achieve a better control performance in the traditional tension control system because the winding speed remains relatively stable while winding circular wire frames. However, it is not quite applicable in the situation of
winding strip frames, such as a stator, since the winding speed changes dramatically and periodically during the winding process[10]. Therefore, the concept of feed-forward control based on PID feedback control is introduced in this paper to realize fast and accurate tension regulation of motor strip stator.

2. Tension Control System

2.1. Mechanical Structure

![Figure 1. Mechanical structure of the tension control system](image)

The mechanical structure of enameled wire tension control system is shown in Figure 1. From the wire source, the enameled wire bypasses the regulating wheel 1, discharging wheel, regulating wheel 2, passing wheel, regulating wheel 3, and is finally wound on the strip wire frame. Due to the tension of enameled wire and spring, swinging rod can swing around O point. The discharge wheel and strip wire frame are attached on the shafts of the discharge motor and winding motor respectively. V-shaped groove is slotted on the outer edge of the discharge wheel and an O-ring is inserted in to increase the friction. As shown in figure1, it is obvious that the variation of tension along the wire will induce the change of tension on the spring, which further leads to the change of swinging angle $\theta$. Therefore, there is a one-to-one relationship between the swing angle of swinging rod and wire tension. It can be derived by using the method mentioned in [2]. In the proposed system, the swing angle $\theta$ is set to be the controlled variable so that the tension can be maintained as long as the $\theta$ is well controlled.

2.2. Control System

The block diagram of control system which consists of the PID controller, feed-forward controller, actuator, sensor, strip wire frame structure and controlled mechanical structure is shown in Figure 2. The error value $e(t)$ is the difference between the set swinging angle $\theta_0$ and the measured angle $m(t)$ from the angular sensor. $e(t)$ was input into the PID controller for the calculation of PID controlled variable $c_1(t)$. Feed-forward controller calculates feed-forward controlled variable $c_2(t)$ by the position of strip wire frame structure. The sum of the two variable is speed control signal applied to actuator, which is the discharge motor in the system. The winding speed of the discharge motor $s_1(t)$ and the winding speed of the strip wire frame $s_2(t)$ are subtracted and input to the controlled mechanical structure to obtain the swing angle value of the swinging rod $y(t)$. 
In the proposed control system, the incremental encoder is selected as the sensor due to the merits of fast responding and high precision. The angle signal is converted by the encoder into a periodic electrical signal, and then further converted into a counting pulse. The number of pulses represents the magnitude of the angle. In addition, a servo motor, which is more stable and accurate than step motor, is employed as the actuator. The controller is the core of the whole control system. It is required to be fast enough for processing. At the same time, it also needs the capacity to realize several pivotal functions, such as pulse capture, PWM signal output and serial port communication. Micro-Controller Unit (MCU) and Programmable Logic Controller (PLC) are two commonly used controllers in current industry. In this paper, the MCU is chosen in the consideration of lower cost.

2.3. Characteristics of the Controlled Object
In order to obtain the transfer function of the controlled object, the swinging rod is fixed at a certain position while the tension on the wire is maintained simultaneously. Afterwards, the discharge motor is driven by the excitation signal from controller to run at 1500r/min for 2ms. The excitation signal can be regarded as a speed pulse signal due to the large amplitude and short duration. The measured swing angle response curve is shown in Figure 3. As the integral of speed equals to the angular displacement, the speed pulse signal can also be approximated as the angular displacement step signal. The response curve in Figure 3 is very similar to the step response curve of the first-order inertial system. Therefore, the transfer function of the controlled object is regarded as the product of the integral part, the pure delay part and the first-order inertia part. The transfer function of the controlled object is established as

$$\frac{X_o(s)}{V_i(s)} = \frac{K}{s(Ts+1)} e^{-\tau s}$$

(1)

where $X_o(s)$ is the output angle image function, $V_i(s)$ is the input speed image function, $K$ is the gain, $T$ is the time constant and $\tau$ is the pure delay time.

As shown in figure 3, the angle remains the same from 0ms to 3ms, which is determined as the pure delay of the controlled object. As for the first-order inertial system, time constant $T$ is the time that takes for the step response to reach 63.2% of the maximum in the steady-state. Additionally, the coefficient $K$ can be obtained according to the final value theorem. $\tau=0.003$, $T=0.0162$ and $K=1.41$ can be derived in equation (1), and the transfer function of the controlled system is

$$G(s) = \frac{1.41}{s(0.0162s+1)} e^{-0.003s}$$

(2)
3. Controller Design

3.1. Improved PID Controller

PID control algorithm is based on the deviation value in the system to calculate proportional, integral and differential value respectively. PID controller has the advantages of simple structure, good stability and convenient adjustment[11]. Particularly, digital PID controller is widely used in the computer control system and its mathematical expression is

\[
u(k) = K_p e(k) + \frac{T}{T_i} \sum_{j=0}^{k} e(j) + T_d \frac{e(k) - e(k-1)}{T}
\]

Where \(u(k)\) is the control variable and \(e(k)\) is the system deviation variable; \(K_p\) is the proportional coefficient and \(T_i, T_d\). \(T\) is the integral time constant, differential time constant, sampling period respectively. Integral coefficient \(K_i\) and differential coefficient \(K_d\) can be further derived as \(K_i = K_p / T_i\) and \(K_d = K_p * T_d\). \(k\) is the sampling sequence index.

The PID control coefficients have great influence on the performance of the controller. In this paper, parameters are set according to Ziegler-Nichols method. Initially, the pure proportional control is taken into consideration to obtain the proportional coefficient and critical period by gradually increasing the proportional coefficient until the system yield an equal-amplitude oscillation transition process.

The traditional PID control algorithm generally has a large overshoot and a long oscillating time. In order to eliminate this deficiency, the traditional PID controller needs to be improved. The improved PID controller according to the absolute value of deviations \(|e(t)|\) and deviation rate \(|\Delta e(t)|\) can dynamically adjust PID parameter, so that controller has different sets of PID coefficients at different stages. The specific adjustment rules are further explained as follows.

1. In the early stage of the control process, \(|e(t)|\) is large, the integral part is removed to prevent integral saturation. Namely, only PD control is applied. At the same time, the value of the differential time constant should be small.
2. In the middle of the control process, \(|e(t)|\) and \(|\Delta e(t)|\) are at an intermediate value. In order to reduce the overshoot and improve the response speed, proportional coefficient should be relatively small.
3. In the later stage of the process control, \(|e(t)|\) and \(|\Delta e(t)|\) are relatively small. In order to improve the precision and avoid oscillation, proportional and integral coefficient values should be increased.

After parameter setting and dynamic adjustment, PID parameter in each stage is shown in table 1.

![Figure 3. Swing angle response curve](image-url)
Table 1. Parameters of PID controller

| PID coefficient | early stage | middle stage | later stage |
|-----------------|-------------|--------------|-------------|
| proportional $K_p$ | 60          | 50           | 70          |
| integral $K_i$   | 0           | 3000         | 5000        |
| differential $K_D$ | 0.3        | 0.5          | 0.8         |

3.2. Feed-forward Controller

According to the invariance principle and the block diagram of tension control system shown in figure 2, the conditions for achieving full compensation can be expressed as

$$G_p(s)G_1(s)G_2(s) + G_3(s)G_4(s) = 0$$

(4)

$$G_p(s) = -G_3(s) / G_1(s)$$

(5)

Where $G_p(s)$ is the transfer function of feedback controller, which is the same as the PID controller mentioned previously. $G_1(s)$ is the function of discharge motor, $G_2(s)$ is the transfer function of mechanical structure, $G_3(s)$ is the transfer function of feed-forward controller, and $G_4(s)$ is the transfer function of the strip frame. Specifically, $G_p(s)G_1(s)G_2(s)$ is the transfer function of feed-forward control channel and $G_3(s)G_4(s)$ is the transfer function of interference channel. $G_1(s)$ can be also regarded as proportional amplification and pure delay. Therefore, transfer function of the strip frame object is the only part that needs to be determined.

The strip wire frame is fixed on the shaft of the winding motor, which drives the strip wire frame to rotate at a uniform speed. For convenience, the speed is defined to be $n(r/min)$ and the angular speed is determined as $\omega = n \pi / 30$. Further more, it is defined that the short side length of the strip wire frame being $2a$, the long side length being $2b$, the diagonal length being $2r$, the angle between the diagonal and the long side being $\theta_1$, and its value is $\arctan(a/b)$ and the angle between the diagonal and the short side is $\theta_2$, and its value is $\arctan(b/a)$.

![Figure 4. Strip wire frame Position 1](image1)

![Figure 5. Strip wire frame Position 2](image2)

![Figure 6. General situation from position 1 to position 2](image3)

Two particular positions of the strip wire frame during the winding process are shown in figure 4
and figure 5. Position 1 is the situation where the long side of the strip wire frame is parallel to the enameled wire. Position 2 is the position where the short side of the strip wire frame is parallel to the enameled wire. Point F in both figures indicates the source of enameled wire. \( \theta_3 \) is the angle \( \angle A_1 FO \) and its value is \( \arcsin(a/l) \). \( \theta_4 \) is angle \( \angle D_2 FO \) and its value is \( \arcsin(b/l) \).

The strip wire frame repeatedly rotates from Position 1 to Position 2 and back with the constant speed when rotating. Consequently, it is sound to simplify the movement model of the strip wire frame by just analyzing the transition between two aforementioned particular positions.

To be more specific, a random position of the strip wire frame in the transition from Position 1 to Position 2 is shown in figure 6. The linear velocity of Point A is \( V_A = r \omega \). Since the linear velocity of enameled wire line speed is the projection of \( V_A \) along the direction, so that the value can be determined as \( V_{line} = V_A \cos(\pi/2 - \angle EAO) \) where \( \angle EAO = \angle AOF + \angle AFO \). If \( \angle AOF = \theta \) and \( \angle AFO = \alpha \) are substituted, \( V_{line} = r \cos(\pi/2 - \theta - \alpha) \) can be eventually derived. It is similar to analyze the transition from Position 2 to Position 1 and it turns out that \( V_{line} = r \cos(\pi/2 - \theta - \alpha) \). Namely, \( V_{line} \) is determined by \( \theta \) and \( \alpha \). \( \theta \) and \( \alpha \) can be respectively derived as follows.

1. \( \theta \), the angle of the strip wire frame at any position

Assuming position 1 is the initial position of the strip wire frame. For convenience, the angle that the strip wire frame rotates from the initial position is defined as \( \Theta \). It is defined that \( \Theta = 0 \) when the strip wire frame is at Position 1 and \( \Theta = \pi/2 - \theta_3 + \theta_4 \) when it is at Position 2. As a result, \( \Theta = \angle A_1 OF + \Theta = \pi/2 - \theta_3 - \theta_4 + \Theta \) as the strip wire frame rotates from Position 1 to Position 2 and \( \Theta = \angle D_2 OF + \Theta - (\angle A_2 OF - \angle A_4 OF) = \Theta - \theta_3 - \theta_4 \) as it rotates back to Position 1 again. Thus, \( \theta \) can be expressed as

\[
\theta = \begin{cases} 
\frac{\pi}{2} - \theta_3 - \theta_4 + \Theta & 0 < \Theta < \pi/2 + \theta_3 - \theta_4 \\
\Theta - \theta_3 - \theta_4 & \pi/2 + \theta_3 - \theta_4 < \Theta < \pi
\end{cases}
\]  

(6)

2. \( \alpha \), the corner of the strip wire frame at any position

As an example, from Position 1 to Position 2, \( \alpha \) can be expressed by following the law of sine and cosine as

\[
\alpha = \arcsin\left(\frac{r \sin \theta}{\sqrt{r^2 + l^2 - 2rl \cos \theta}}\right)
\]  

(7)

\( \alpha \) can be further solved by using MATLAB if \( a = 4 \text{mm}, b = 20 \text{mm}, l = 320 \text{mm} \) substituted into. The curve of linear velocity versus time when the rotational speed \( n = 300 \text{r/min} \) is shown in Figure 7. Furthermore, in order to estimate the precision of the mode being built above, the length of wound enameled wire is compared in between experiment and simulation. Specifically, the enameled wire is connected to both encoder and the strip wire frame. While winding, the length of enameled wire wound can be precisely derived from the encoder. The result is plotted in figure 8, where two curves are highly identical with the maximum difference of 2mm. It indicates that the established model is accurate.
4. Simulation and Experiment
The block diagram constructed in SIMULINK/MATLAB is shown in Figure 9. When the rotational speed \( n \) is 900 r/min, the pure PID and feed-forward feedback control modes are simulated respectively. The simulation results are shown in Figure 10. Due to the rotation direction of the discharge motor is limited, at the initial stage, the swing angle change is only caused by the rotation of wire frame, rather than the controller, so that two curves are almost identical. In the transition process, the maximum overshoot of pure PID is 4.1°, which is significantly greater than 1.5° of feedforward feedback control. In the steady state process, the fluctuation range of swing angle when the pure PID is applied is ±2.1°. Whereas, only ±0.1° fluctuation is detected when feed-forward feedback control is added. It can be concluded the system performs much better in the whole process when the feed-forward control is introduced.

The winding tension control experiment is carried out on the prototype. As setup, the enameled wire with diameter of 0.35mm is used and the speed of the wire frame is set at 900r/min. The control system with and without feed-forward loop are separately experimented. As the plots depicted in Figure 11, the maximum overshoot of swing angle is 5.2° when the system is without feed-forward loop, and the fluctuation range is ±3.0° in the steady stage of the operation. As a comparison, the maximum overshoot and the fluctuation range of the swing angle are 0.88° and ±0.53°, respectively. Obviously, the system can reach the set value faster and smoother with the help of feed-forward control. Meanwhile, the real system is highly consistent with the simulated model when comparing results shown in figure 10 to figure 11.
According to the one-to-one correspondence between the swing angle and the tension discussed in section 1.1, when the swing angle is set at 45°, the corresponding set tension along the enameled wire can be calculated to be 500g. Based on the set tension value, 10.0g maximum overshoot of the feed-forward feedback control and ±6.1g winding fluctuation range can be observed from figure 11. Since 500g tension value is already the highest demand on winding 0.35mm enameled wire at 900r/min standard tension in most conventional industrial applications, the proposed controller can well meet the practical requirements.

Winding performances at 300r/min, 600r/min and 900r/min winding speed are compared in figure 12 while the feed-forward control is involved. The time that three operations take to reach the set value is different due to the different rotation speed. However, in the steady stage, the fluctuation ranges of the swing angle at different rotating speed are all around ±0.5°. This result confirms that the fluctuation of the swing angle is not related to rotation speed.

Performance of tension regulation is also verified by changing springs with different elastic coefficient. Since 500g tension is close to the limitation of tension for 0.35mm enameled wire, 0.7mm enameled wire is used in further experiment when the base tension continues to be increased to 600g, 900g and 1600g. The control performances are compared and shown in figure 13 at the winding speed of 600r/min. Apparently, it takes almost that same time period for the swing angle reaches the set value under different set tension values. At the steady stage, the fluctuation range of the swing angle are both...
±0.5° under the base tension of 600g and 1000g. Even though the fluctuation range increases to ±1° when the base tension value is increase to 1600g, the control performance is still better than that of pure PID control as shown in figure 11.

5. Conclusion
In this paper, the tension control of enameled wire while winding strip stators is studied. The PID algorithm is employed in the proposed system. Both simulation and experiment are compared between the systems with and without feed-forward control. Several key conclusions can be drawn as follows.

1) The feed-forward control can significantly improve the control performance. The maximum tension fluctuation is ±6.1g throughout the whole winding process under the situation that winding speed is 900r/min and base tension value is 500g. This is 80% less than the result derived under the same situation in the system without feed-forward control.

2) The performance of the feed-forward control is independent of the winding speed when the winding parameters are reaching the upper limitation of winding 0.35mm enameled wire. Namely, the set tension value is 500g and the winding speed is 900r/min.

3) When increasing the tension of enameled wire, the swing angle fluctuation will increase. The control performance will be deteriorated if the tension reach to the limit. For instance, while winding 0.7mm enameled wire, the fluctuation of swing angle will increase from ±0.5° to ±1° if the base tension is increased from 600g to 1600g.

6. References
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