Research on Tension Control System of Reciprocating Winding

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Abstract. When the enameled wire is wound onto the poles of the motor stator or rotor, the winding quality hugely relies on the control precision of the tension. Therefore, it is necessary to control the tension of the enameled wire in winding process. A tension control system is built with single chip microcomputer, the encoder and the servo motor. The PID feedback controller and feedforward controller are combined to form feedforward feedback controller, which using feedback information of swing angle deviation and feedforward information of wire frame position to adjust the pay off speed dynamically and control tension of enameled wire further. A procedural experimental modelling method is discussed in order to identify the feedforward model. The experiment is performed, it is found that in the typical situation of setting tension 1500 g, the tension fluctuation rate of the PID controller with feedforward model is only 2%, which is far better than that of pure PID controller with a fluctuation rate of 14%. The result shows that the proposed experimental modelling method hosts the characteristics of good accuracy, universality and applicability.

1. Introduction

During the manufacture process of the motor, the enameled wire should be essentially winded onto the poles of stator or rotor. The winding quality hugely relies on the control precision of the tension. Therefore, it is necessary to control the tension of the enameled wire in the winding process. With the development of motor towards high performance, a good tension control system is necessary.

There are three common winding methods for the different products and the production processes: the flat winding, the flying fork winding and the reciprocating winding. Further, the reciprocating winding may be subdivided into the reciprocating outer winding and the reciprocating inner winding. Generally speaking, the difficulty of tension control is related to the change of the line speed of the enameled wire during winding. The more violent the speed change is, the more difficult the tension control is. Among above three winding methods, the line speed fluctuations of the reciprocating winding are undoubtedly the most violent, so the tension of which is the most difficult to control.

The most common method in the tension control is PID control[1,2,3,4,5], which is simple in principle and easy to implement. When the structure of the controlled object is simple or the winding speed is relatively low, the PID control method can achieve a good control effect. Song et al. studied the tension control of the flat winding for a circular skeleton[1]. On the basis of measuring the characteristics of the controlled object, they adjusted the PID parameters continuously by means of test, simulation and field debugging. The PID controller designed finally achieved a good effect. In recent years, sliding mode control, neural network control, genetic optimization and other methods were also used to tension control[6,7,8,9,10]. For example, He et al. put forth the online and offline genetic optimization of the tension system with fuzzy control method[6]. They adopted the genetic
algorithm to optimize the membership function offline, and then utilized the super-generation transfer
algorithm to optimize the scale factor online, which brought about a good real-time tension control on
the experimental platform.

The PID control method is not so ideal if the wound object is complex in structure or the winding
speed is high. In comparison, the advanced neural network control is an alternative. However the
algorithm of the neural network control is complex, the amount of calculation is large and the
decoupling is difficult[6]. In order to achieve a real-time performance, the controller should possess a
strong computing power. Zhao et al. [11] put into effect a scheme of PID control with a feedforward
model, with which the problem of the tension fluctuation in flat winding for rectangular skeleton was
well solved. However, the feedforward model was established through theoretical analysis, so there are
also some shortcomings such as complex modelling process and poor generality, which restricted its
application. This paper studies an experimental method to simplify the feedforward modelling process
in the hope of achieving the similar control effect as that of the theoretical model.

2. Overall Structure of Tension Control System

2.1. Mechanical Structure
The mechanical structure of the enameled wire tension control system is shown in figure 1. From the
wire source, the enameled wire bypasses three guide wheels, one pay off wheel and one passing wheel,
and is finally wound on the pole of the motor work piece in winding machine. The rod call swing rod
can swing around the point O under the joint force from the enameled wire and spring. The pay off
wheel is installed on the shaft of the pay off motor. There is a V-shaped groove on the outer edge of
the pay off wheel, and an O shaped ring is embedded inside to increase the friction. It is obvious that
when the swing angle of the swing rod increases, the restoring force of the spring increases, and the
corresponding tension of the enameled wire also increases; and vice versa. There is a one-to-one
correspondence between the swing angle of the swing rod and the tension of the enameled wire, which
has been discussed by Song et al.[1]. If taking the swing angle as the controlled variable of the control
system, the tension of the enameled wire can be kept constant as long as the swing angle is controlled
to be constant.

![Figure 1. Mechanical structure of the tension control system](image1)

![Figure 2. Schematic diagram of reciprocating winding](image2)

2.2. Structure and Characteristics of Reciprocating Winding
The schematic diagram of the reciprocating winding is shown in figure 2. The enameled wire from
tension control system passes through the guide needle, goes out from the nozzle, and is finally
winded on the skeleton. During the winding process, the guide needle moves up and down, while the
skeleton swing around the axis. These two movements execute alternately in sequence. If regarding
the skeleton as the reference, the guide needle circles around the skeleton forming the motion track as A-B-C-D-A in figure 3. One turn of the enameled wire is wound on the skeleton when the guide needle runs a round. The round number of the guide needle per minute is the working speed of the reciprocating winding machine.

During the winding process, the movement of the guide needle and the skeleton can be divided into four stages: the guide needle moves downward, the skeleton swings, the guide needle moves upward and the skeleton swings reverse. The line speed of the enameled wire is different in different stages. It is the largest in the stage of the guide needle moving downward, but almost zero in the stage of the guide needle moving upward. The line speed of the other two stages is between these two. On the whole, the line speed fluctuates severely in a cycle round of the guide needle, which makes it much more difficult to control the wire tension than that of flat winding by Zhao et al.[11]

2.3 Control System
The block diagram of tension control system is shown in figure 4, which mainly includes the PID controller, the feedforward controller, the pay off motor, the encoder, the motor skeleton and the controlled mechanical structure. With the encoder, the actual angle value of the swing rod is measured and subtracted by the set value to obtain the swing angle error value. The PID controller takes it in and calculates the PID control value. At the same time, the feedforward controller calculates the feedforward control value according to the current position of the guide needle. These two values add together to get the final control value, which is the speed control signal acting on the actuator, namely the pay off motor.

The transfer function of the payoff motor may be regarded as a proportional amplification unit plus a pure delay unit. The transfer function of the controlled mechanical structure may be regarded as the combination of a integral unit, a pure delay unit and a first-order inertia unit[1]. The transfer function of the payoff motor $G_1(s)$ and that of the controlled mechanical structure $G_2(s)$ can be measured respectively by the experimental method[1] has follows

$$G_1(s) = 0.000371 e^{-0.0015 s}$$

$$G_2(s) = \frac{380}{s(0.0162 s + 1)} e^{-0.0015 s}$$

Based on the error of the system, the PID controller calculates the feedback control value using proportional, integral, and derivative modes separately. PID controller has the advantages of simple structure, good stability, and convenient adjustment. The mathematical expression of the digital PID controller is

![Figure 3. Guide needle movement track](image)

![Figure 4. Block diagram of tension control system](image)
$$u(k) = K_p e(k) + \sum_{j=k}^{\infty} e(j) + T_d \frac{e(k) - e(k-1)}{T}$$

(3)

Where \(u(k)\) is the control value, \(e(k)\) is the system error, \(K_p\) is the proportional coefficient, \(T_i\) is the integral time constant, \(T_d\) is the derivative time constant, \(T\) is the sampling period and \(k\) is the sampling sequence number.

The combination of the proportional coefficient, the integral coefficient, and the differential coefficient has a great influence on the performance of the control system. The Ziegler-Nichols method is used to determine these coefficients. On the condition of pure proportional control, gradually increase the proportional coefficient until a constant amplitude oscillation of the system appears, then these coefficients can be obtained according to the proportional coefficient and critical period at that condition.[12]

The PID feedback control works on the basis of the error. The advantage is that no matter what causes the change of the controlled variable will be reflected in the error, with which the PID controller could calculate the control value. Meanwhile the disadvantage is that there is always a certain lag. However, the control principle of the feedforward control is totally different. The basic idea of the feedforward control is to measure the interference, and then generate the appropriate control value to drive the actuator and counteract the effect of the interference in advance.

In figure 4, the transfer function of the interference channel is \(G_i(s)\), and the transfer function of the feedforward control channel is \(G_{ff}(s)\). The conditions to a full compensation of the interference are

\[G_p(s)G_i(s)G_e(s) + G_e(s)G_e(s) = 0\]

(4)

\[G_p(s) = \frac{G_e(s)}{G_i(s)}\]

(5)

To design the feedforward controller \(G_{ff}(s)\), it is only needed to get the transfer function of the skeleton winded \(G_i(s)\). Theoretical modelling is an option, but the modelling process is complex and time-consuming [11]. Moreover, the model has to be rebuilt if the geometric parameter of the skeleton changes. In order to overcome these shortcomings, experimental feedforward modeling method is proposed.

3. Experimental Modelling

3.1. Experimental Modelling Method

The guide needle moves periodically and relatively to the skeleton. The winding machine will send out a signal at a fixed position of each winding cycle, which is regarded as the zero position of the guide needle movement. Starting from the zero position, a movement cycle of the guide needle is divided into \(N\) positions in equal proportion to the cycle time. Line speed of the enameled wire at position \(i\) is marked as \(V(i, n_0)\), where \(i=0,1,2...N-1\), and \(n_0\) is the working speed of the winding machine. If the working speed changes, line speed changes in proportion. Therefore, for a working speed \(n\), line speed of the enameled wire at position \(i\) is

\[V(i, n) = \frac{n}{n_0} V(i, n_0)\]

(6)

For the convenience of calculation and comparison, \(V(i, n_0)\) is normalized to the condition of \(n_0=1\ rev/min\), which is called the feedforward control model. In the actual operation, what needs to do is to scale up according to the real speed.

The process of the experimental modelling is as follows, all the steps are controlled by the controller.

1) Drive the guide needle to the zero position, and run the pay off motor at the same time to adjust the swing rod at the position where swing angle is the set angle value. Divide a winding cycle into \(N\)
equal positions. This is the start point of the modelling.

2) Keep the pay off motor not running, move the guide needle slowly from position i to next position i+1. As a section of the enameled wire is wound on the skeleton, the swing angle increases smoothly to a stable value.

3) Keep the guide needle not moving, run the pay off motor with the input pulse from the controller. As the the enameled wire is paid off, the swing angle of the swing rod reduces. Once the swing angle decreases to its set value, shut the input pulse.

4) Record the position of the guide needle at this moment, and the pulse number from the controller to the pay off motor at last step. If the guide needle does not move a full cycle, repeat 2-4.

5) Process the data and get the feed-forward model.

In the process of experimental modelling, N pulse data are recorded, in which data i represents the number of pulses from position i to position i+1, and the value is recorded as m(i).

3.2. Data Processing and Modelling Result

Figure 5 is the pulse count number during modelling. The abscissa in the figure is the angle position I corresponding to a moving cycle of the guide needle, while the ordinate is the pulse number m(i) from position i to next position i+1, which is fed to the pay off motor. It is clear that the pulse number m(i) at many positions is zero, which means that the rotating speed of the pay off motor is zero at these positions. This phenomenon is caused by the resolution of the encoder. If the swing rod angle increment is less than the resolution of the encoder, it is not detected, hence there is no pulses input to the pay off motor.

The raw data is figure 5 is not applicable. In order to extract the model information accurately, an effective method is to distribute evenly the data of non-zero pulse increment position to the zero pulse position. For the case shown in equation (7)

\[
m(i) \neq 0, \quad m(i) \neq 0, \quad m(i) = 0, \quad i_1 < i < i_2
\]

There are pulses count at positions i_1 and i_2, while the pulse count at each position between i_1 and i_2 is zero. The pulse m(i) at position i_2 can be distributed evenly to the positions between i_1 and i_2, including i_2 but exclude i_1, as shown in equation (8).

\[
m'(i) = \frac{m(i_2)}{i_2 - i_1}, \quad i_1 < i \leq i_2, \quad n(i) = \frac{m(i)}{i_2 - i_1}, \quad i_1 < i \leq i_2
\]

The processed pulse increment data is shown in figure 6, compared with the original data in figure 5, which can reflect the reciprocating winding model better.
the working speed of the winding machine. As a result, the Fourier series can be used to extract specific periodical frequency components. The pulse number curve in a period with \( N \) points inside can be expressed by Fourier series as follows

\[
f(i) = A_0 + \sum_{n=1}^{\infty} A_n \cos\left(\frac{2\pi n i}{N} - \phi_n\right)
\]

Finally, the feedforward mathematical model in the form of Fourier series is shown in equation (10), in which only the even terms of the first 6 orders are kept. The curve is also shown in figure 6. It is found that the continuous mathematical model can reflect the experimental data accurately.

\[
f(i) = 0.5050 + 0.5621\cos\left(\frac{2\pi i}{N} + 0.8629\right) + 0.3976\cos\left(\frac{4\pi i}{N} + 1.3177\right) + 0.1131\cos\left(\frac{6\pi i}{N} + 2.4629\right)
+ 0.0126\cos\left(\frac{8\pi i}{N} + 2.2733\right) + 0.0879\cos\left(\frac{10\pi i}{N} - 0.6843\right) + 0.0449\cos\left(\frac{12\pi i}{N} + 1.4204\right)
\]

4. Reciprocating Winding Experiment and Result Analysis

The winding experiment is carried out in a winding machine. As shown in figure 7, an armature with 6 poles is used for winding. The outer diameter of the armature is 60mm. Each pole is a skeleton and should be wound multiple turns of enameled wire. The winding mode is external reciprocating winding, or external winding.

In the winding experiment, the diameter of the enameled wire is 0.35mm, the set tension is 1500g, and the working speed is 600 rev/min. The PID controller with and without feedforward model are used to control the tension respectively. The fluctuations of the swing angle are recorded in the winding process. The results are shown in figure 8 and figure 9 respectively. It is found that the error of swing angle from the set value is about ±7.0º if only pure PID controller is used. However, the error is about ±1.0º if the PID controller with feedforward model is used. After conversion with the method by Song et al.[1], the corresponding tension deviation is ±210g and the tension fluctuation rate is 14% for the pure PID controller, while these data are ±30g and 2% for the PID controller with feedforward model.

The experimental results show that the tension of the enameled wire fluctuates sharply in the winding process with pure PID controller, which cannot meet the requirements of high-quality winding. On the contrary, the PID controller with feedforward model could achieve good tension control effect.

5. Conclusion

This work studies the tension control problem of the reciprocating winding for the motor skeleton. The tension control system is established, and the PID controller with the feedforward model is designed. In order to avoid the difficulty of the theoretical feedforward modeling, an experimental modeling method is put forward. The experiment on a winding machine is performed and the control effect of
PID controller with and without feedforward model is compared. The result shows that the tension fluctuation rate of the PID controller with the feedforward model is 2%, which is far less than that without the feedforward model, say 14%. The method to get the experimental model may be programmed executed, making it easy to popularize to the other shaped skeleton or winding method.

![Figure 8. Deviation of swing angle with pure PID controller](image1)

![Figure 9. Deviation of swing angle with the PID controller with feedforward model](image2)

6. References

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