Design of Turntable Servo Control System Based on Sliding Mode Control Algorithm

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Abstract. With the development of national defense weaponry and equipment level, higher requirements are put forward for the servo control system. The traditional PID algorithm is difficult to satisfy the target; this paper proposes a sliding mode control algorithm. Firstly, the working principle is analyzed, the DC motor model is established, the sliding mode controller is designed, and the boundary layer method is used to weaken the chattering of sliding mode control, the Stribeck friction model is used at the same time, and the simulation and experimental results is given. The experimental results show that the tracking error of the sliding mode control is 0.36° and the tracking error of the PID control is 0.675° under the same conditions, the results show that the sliding mode control algorithm is better than the PID control algorithm in the robustness and tracking performance.

Keywords: Turntable · Servo system · PID control algorithm
Sliding mode control algorithm

1 Introduction

Nowadays, in the field of aviation, spaceflight, navigation, the world competition for military supremacy is becoming increasingly acute, the performance requirements for the navigation and guidance equipment is improved continuously. As one of the key equipment of the guidance weapon, the turntable also needs higher dynamic performance. The way to improve the control method to improve the tracking accuracy of the turntable has been an urgent problem to be solved [1].

As the motor is often rotated a very small angle when the turntable works, the friction torque, which is often neglected in general motor control, cannot be ignored in the turntable control. So many scholars use various methods to control and compensate the influence of friction torque. Friction is a very complex nonlinear phenomenon, and the traditional control algorithm such as PI control and PID control is not enough to make up for its influence [2]. Li pointed out that although the traditional PID method is simple, well stability algorithm, it is easy to cause the system overshoot or shock [3]. Since the 80s of last century, the research in this field has grown significantly, and many new friction models and friction compensation methods have emerged, and they have been successfully applied to the servo control system [4]. Yan et al. separated the

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friction torque from the load torque and designed an adaptive back stepping controller to achieve the targeted compensation of friction torque [5]. Zhang et al. used the dual observer to observe the changing state of the LuGre friction model aimed at the onboard battery servo control system, and designed an adaptive dynamic compensation algorithm to compensate the nonlinear disturbance of the friction force, and the tracking accuracy is improved [6]. Although the LuGre friction model can describe the dynamic characteristics of the friction force in the servo control system accurately, it is very difficult to measure the parameters of the model as for its high nonlinearity [7]. Yan et al. made a detailed analysis of Coulomb friction model, Stribeck friction model and Lugre friction model, and pointed out that the Lugre model has many parameters and is very difficult to be measured, and the Stribeck friction model is more accurate than the Coulomb friction model and can achieve 90% approximation of the entire friction characteristics [8].

In this paper, a sliding mode switching function and a sliding mode controller are designed, the boundary layer method is used to suppress the chattering in the sliding mode control. The simulation results show that the boundary layer method can restrain the chattering of sliding mode. At the same time, the sliding mode controller is compared with the PID controller and the Stribeck friction model is used. The simulation results show that the sliding mode controller has good tracking performance and robustness. Finally, the turntable servo control device is designed, debugged and analyzed by the LabVIEW PC, and achieved good experimental results.

2 The Working Principle and Design of Sliding Mode Controller

2.1 The Working Principle of Sliding Mode Controller

The schematic diagram of the sliding mode is shown in Fig. 1. It can be seen that the design of sliding mode control system is mainly divided into two parts; one is on the sliding surface movement, also called sliding mode movement, corresponding to the switching function; the other is outside the sliding surface movement, also called reaching movement, corresponding to the sliding mode control rate. Which the sliding surface determines the performance of sliding mode control, influences the robustness of sliding mode control, and the reaching law determines the reaching method from any state to the sliding surface, which influences the rapidity and accessibility of sliding mode control.

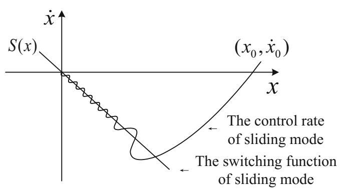


Fig. 1. Schematic diagram of the sliding mode state

Linear sliding surface is the most common sliding surface, and the system has the characteristic of reducing order on the sliding surface. The design of linear sliding surface can be realized by the method of optimal control and pole placement, which is simple and easy to design, and it is widely used in various systems. The linear sliding surface expression is shown in the formula 1, in which $S(x)$ is the sliding surface; C is the sliding mode coefficient; x is the system state.

$$S(x) = C\dot{x} + x \tag{1}$$

2.2 The Design of Sliding Mode Controller

(1) The design of the switching function. The dynamic structure of DC motor under rated excitation is shown in Fig. 2.

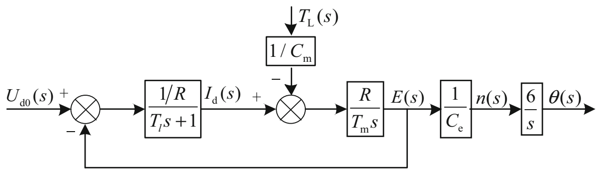


Fig. 2. The dynamic structure of DC motor under rated excitation

According to the model, the relationship between the input voltage and the motor current is shown:

$$[U_{d0}(s) - E(s)] \cdot \frac{1/R}{T_l s + 1} = I_d(s) \tag{2}$$

Through the deformation, taking the position, speed, current as the state variable, the input voltage, load torque as input variables, which can be converted to a state diagram, as shown in Fig. 3.

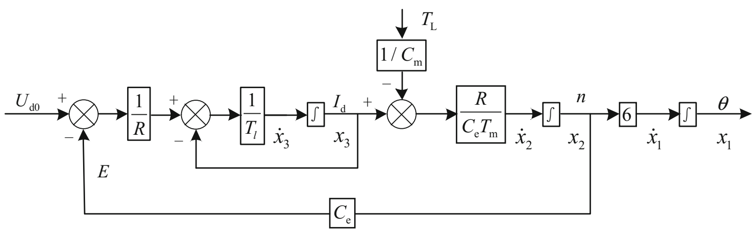


Fig. 3. The state transition diagram of DC motor

If the friction resistance and no-load torque are ignored, the state equation $\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u$ can be shown in formula 3.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 6 & 0 \\ 0 & 0 & \frac{R}{C_e T_m} \\ 0 & -\frac{C_e}{L} & -\frac{1}{T_l} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} U_{d0} \tag{3}$$

Suppose the sliding mode switching function is $\sigma = S_1 x_1 + S_2 x_2 + S_3 x_3$, when the system reaches the switching plane, $\sigma = 0;\ \dot{\sigma} = 0$, the sliding mode equation is shown:

$$\begin{cases} \dot{x}_1 = (A_{11} - A_{13} S_3^{-1} S_1) x_1 + (A_{12} - A_{13} S_3^{-1} S_2) x_2 \\ \dot{x}_2 = (A_{21} - A_{23} S_3^{-1} S_1) x_1 + (A_{22} - A_{23} S_3^{-1} S_2) x_2 \end{cases} \tag{4}$$

Set $K_1 = S_3^{-1} S_1$, $K_2 = S_3^{-1} S_2$, which can be arbitrarily determined by pole placement. Set $S_3 = 1$, and $\mathbf{S} = [K_1 \quad K_2 \quad 1]$. Substituting the data, it can be got that

$$\mathbf{A} = \begin{bmatrix} 0 & 6 & 0 \\ 0 & 0 & 31.609 \\ 0 & -171.429 & -314.286 \end{bmatrix} \quad \mathbf{B} = \begin{bmatrix} 0 \\ 0 \\ 142.857 \end{bmatrix} \tag{5}$$

According to the sliding mode state equation, it can be got that $s^2 + 31.609 K_2 s + 198.654 K_1 = 0$. We assume that the system does not overshoot, assume that the system has two identical real roots $s_{1,2} = -15.805 K_2$, and because of the discriminant equals zero we can conclude $K_1 = 1.317 K_2^2$, we hope that we can obtain the characteristic as good as the PID regulator in the absence of friction and disturbance. It can be calculated that $K_1 = 0.396$, $K_2 = 0.548$, so the sliding mode switching function is that:

$$\sigma = 0.396 x_1 + 0.548 x_2 + x_3 \tag{6}$$

According to the state equation, it can be written:

$$\sigma = 0.396 x_1 + 0.091 \dot{x}_1 + 0.00527 \ddot{x}_1 \tag{7}$$

(2) The design of the sliding mode controller. Choose the exponential reaching law:

$$\dot{\sigma} = -k\sigma - \eta \operatorname{sgn}(\sigma) \quad (k > 0, \eta > 0) \tag{8}$$

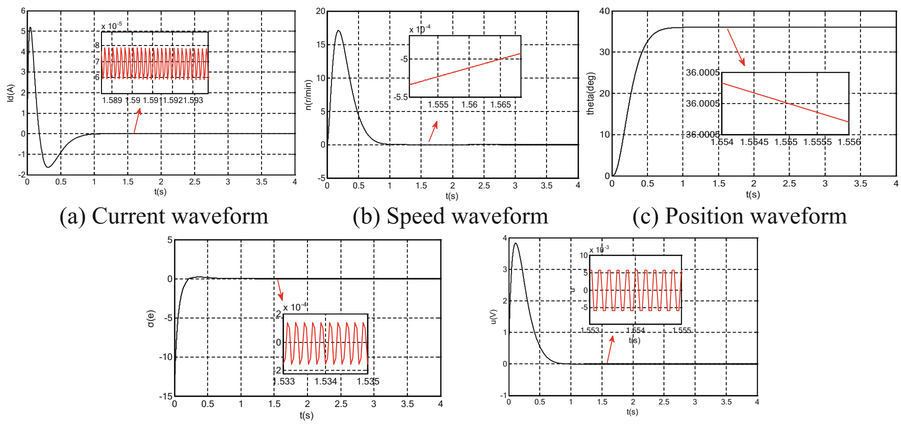
According to the definition of sliding mode switching function, it can be seen that $\dot{\sigma} = \mathbf{S}\dot{\mathbf{x}} = \mathbf{S}(\mathbf{A}\mathbf{x} + \mathbf{B}u)$, which is used to form the controller expression:

$$u = -(\mathbf{SB})^{-1} [\mathbf{SAx} + k\sigma + \eta \operatorname{sgn}(\sigma)] \tag{9}$$

Substituting the data, we can obtain that:

$$U_{d0} = -0.007 \times [-169.053x_2 - 296.964x_3 + k\sigma + \eta \mathrm{sgn}(\sigma)] \tag{10}$$

When $k = 20$, it has good reaching speed. Since the sliding mode switching function uses the deviation, the overall jitter is small, so we choose $\eta = 5$. In order to form a contrast with the PID controller, MATLAB is used to simulate the characteristics of the step, given a 36° simulation results shown in Fig. 4. It can be seen that the switch function, and the controller output form a high frequency jitter, while the speed, position do a low frequency swing in the steady-state value near the micro amplitude. On the one hand, the rotary inertia of the turntable is too large and the speed is slow; On the other hand, the current feedback is introduced, and the amplitude of the current is small. At the same time, the speed feedback and position feedback are introduced to make the change from current to position smaller and smaller.



(a) Current waveform (b) Speed waveform (c) Position waveform

(d) Switching function waveform (e) Controller output waveform

Fig. 4. The simulation chart of the step characteristics of sliding mode control

2.3 Boundary Layer Method to Suppress the Chattering of Sliding Mode

In the sliding mode control, the existence of the sign function will cause the chattering of the input control. In order to eliminate the jitter, a thin boundary layer can be set near the sliding mode surface, so that the output can be controlled to the continuous function between the two boundary layers, as shown in Fig. 5.

From the analysis above, it can be shown that the expression of the boundary layer method is actually a symbolic function, as shown in formula 11. When the sliding mode function enters between the boundary layers, the system will be switched from the switching state to the continuous state, that the system can be approximated as the sliding surface.

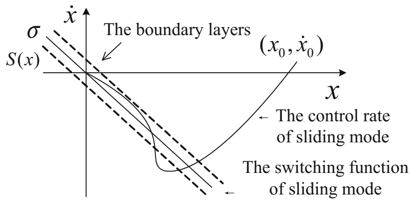
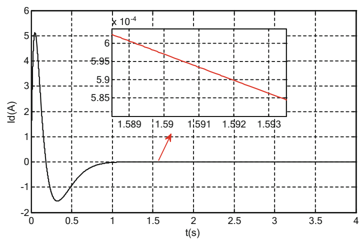


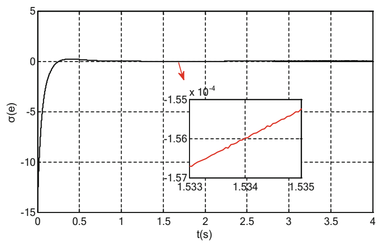
Fig. 5. The boundary layers in sliding mode

$$sat(\sigma) = \begin{cases} \sigma/\phi & |\sigma| < \phi \\ \sigma/|\sigma| & |\sigma| \geq \phi \end{cases} \tag{11}$$

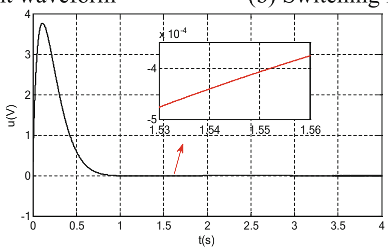
If the boundary layer is too large, the constraints of system dynamics will be reduced to the sliding surface, and the robustness will be reduced. If the boundary layer is too small, the chattering suppression ability will be reduced to the boundary layer. Take the saturation function instead of the sign function; the system has a small chattering and good robustness when taking the boundary layers, as shown in Fig. 6. Compare Fig. 4 with Fig. 6, the state of the system is fast on the sliding surface $\phi = 0.01$, form the high frequency sliding mode chattering in Fig. 4(d), but the system is very slow to approach, cross, away from the sliding mode switching plane, only to reach the boundary layer will change the direction of movement in Fig. 6(b). It can be seen that the dither frequency of the system is greatly reduced.



(a) Current waveform



(b) Switching function waveform



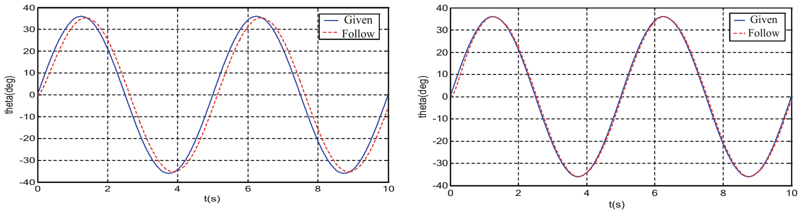
(c) Controller output waveform

Fig. 6. The simulation chart of the sliding mode control using saturation function

3 The Performance Analysis of Sliding Mode Controller

3.1 The Tracking Characteristic Analysis

Without considering the friction resistance, the sine wave with the period of 5 s and an amplitude of 36° (Generally, the ship's swing period is not less than 8 s, where the 5 s analysis can be used to cover most of the swing) is simulated by PID controller and sliding mode controller respectively, and the following characteristics are shown in Fig. 7. In Fig. 7 the actual amplitude of PID is given 1, and here magnified 36 times for comparison. Compared with Fig. 7(a) and (b), the tracking performance of the sliding mode controller is much stronger than that of PID controller that is because the sliding mode surface contains the first derivative and the two derivative of the error, which can get the movement trend of control input effectively, so as to produce better following characteristics.



(a) The PID controller (b) The sliding mode controller

Fig. 7. The comparison of tracking characteristics between the PID controller and the sliding mode controller

3.2 The Robustness Analysis

After adding the Stribeck friction to the system, the sketch map of the sliding mode controller is shown in Fig. 8. Compared with Fig. 8 and Fig. 7(b), when the Stribeck friction model is taken into account, the following characteristics of the sliding mode controller are almost unchanged, which shows that the sliding mode controller has good robustness. Parameters of Stribeck friction model in simulation are measured in practice.

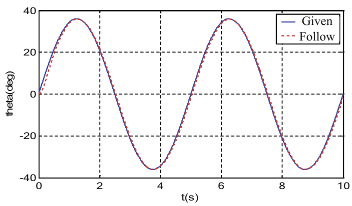


Fig. 8. The tracking characteristics of sliding mode controller with friction

4 The Design and Result Analysis of Turntable Servo Control System

4.1 The Design of Turntable Servo Control System

Combined with the previous analysis, this paper designs the turntable servo control device, including hardware circuit and software PC, etc. Hardware circuit consists with ARM controller as the core, combined with the driver board and other peripheral circuit. The software communicates with the hardware circuit by LabVIEW, and debugs parameters.

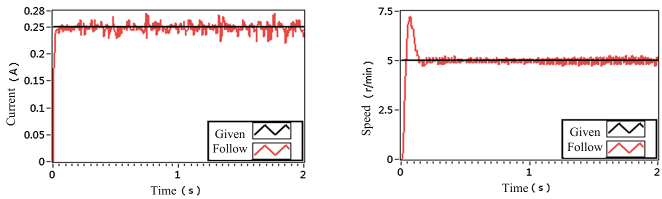
The paper choose an absolute PID (non-incremental PID) as the PID regulator, the expression is as follows:

$$uk = ek * Kp + eksum * Ki \tag{12}$$

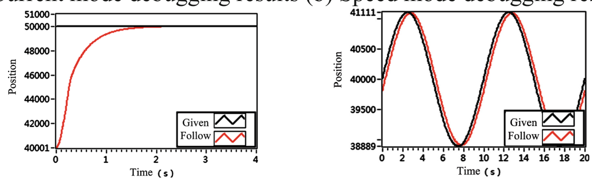
In order to validate the designed the sliding mode controller, the PID algorithm is compared. The sliding mode controller has no current loop, speed loop and position loop, but it still needs to obtain the current, speed and position. As a result, the current sampling filter, current sampling zero correction program are hold.

4.2 The Experimental Results Analysis

The servo control device is connected to the turntable for debugging. Open the parameter setting interface of LabVIEW host computer, and download the parameters to the lower machine through the serial port. Four working modes are set up respectively, and the results of the four modes are shown in Fig. 9, and it can be calculated that the maximum error is about 0.675°.



(a) Current mode debugging results (b) Speed mode debugging results



(c) Position mode debugging results (d) Following mode debugging results

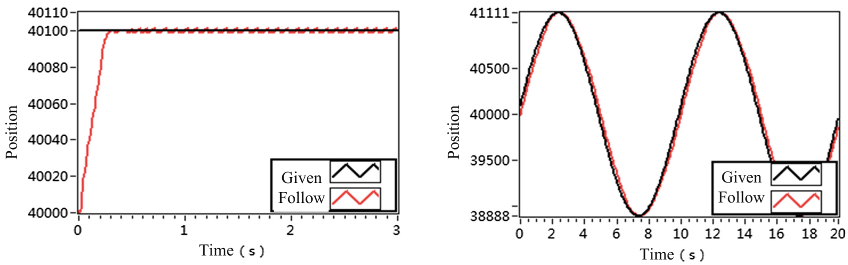
Fig. 9. Turntable PID control algorithm debugging results

In the debugging process of sliding mode control algorithm, because of the algorithm own reasons, there exists no elimination of the sliding mode chattering, and the sliding mode controller has no independent current loop and speed loop, so it can only carry on the position debugging and the simulation follow experiment. In the experiment, the first order differential and second order differential make the system oscillate seriously, so omit the second order differential and inhibit the first order differential then choose the sliding mode switching function as shown in formula 13. In the exponential reaching law, in order to guarantee the reachability of the system, it should satisfy $\eta > 0$ in theory, and the position deviation is an integer in the actual system, there will be no decimal tending to zero, so $\eta = 0$ is still suitable for the requirements of accessibility. In order to reduce the current buffeting, accelerate the response speed, and increase the parameter of exponential reaching law, the output expression of sliding mode control is chosen as the formula 14 finally.

$$\sigma(e) = 0.396e + 0.045\dot{e} \tag{13}$$

$$U_{d0} = -0.007 \times [-169.053x_2 - 30x_3 + 200\sigma] \tag{14}$$

The result is obtained in position mode of sliding mode control, as shown in Fig. 10 (a). When reaching the steady state, there exists some chattering, and the results of the simulation following mode is shown in Fig. 10(b), and it can be calculated that the maximum error is about 0.36°.



(a) Position mode debugging results (b) Following mode debugging results

Fig. 10. Turntable sliding mode control algorithm debugging results

Compare Fig. 9(d) with Fig. 10(b), it can be seen that the sliding mode control algorithm has better robustness and tracking performance than the PID control algorithm.

5 Conclusion

In this paper, the sliding mode controller of servo control system is established. Firstly, the working principle is analyzed; the DC motor model is established, the sliding mode controller is designed, the sliding mode switching function is designed by pole placement method, the sliding mode controller is designed with the exponential reaching law, and the boundary layer method is used to weaken the chattering of sliding mode control. At the same time, the simulation model is built in Simulink, and the Stribeck friction is added, and the simulation results show that the sliding mode controller has good tracking performance and robustness. Finally, the turntable servo control system is designed; LabVIEW is used to write the host computer, to control ARM lower machine through the serial port, so as to control the servo motor. The experimental results show that the tracking error of the sliding mode control is 0.36°, and the tracking error of the PID control is as high as 0.675°, which proves that the sliding mode control algorithm has better robustness and tracking performance than the PID control algorithm. However, the sliding mode control algorithm has a large buffeting current, and the way to coordinate these coefficients and reduce the buffeting current is the focus of the next study.

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