Research on Sliding Mode Control of Two-phase Hybrid Stepper Motor Based on New PI Current Algorithm

Yinxin Lv, Chen Xu, Haohao Guo, Yancheng Liu*

School of Marine Engineering, Dalian Maritime University, Dalian, 116026, China

*Corresponding author's e-mail: liuyc3@163.com

Abstract. This paper aiming at improve the dynamic and static performance and system robustness of the stepper motor servo control system, a control method based on sliding mode is proposed. It can effectively improve the problems of low-frequency vibration and serious torque fluctuation of the stepper motor. At the same time, a new PI current algorithm related to the motor speed is designed. The new PI current algorithm not only ensures the current tracking performance but also increases the bandwidth in the process of speedy response. Compared with the conventional PI current control algorithm, the simulation results show that the new PI current algorithm has a faster response and higher control accuracy, which show that the new PI algorithm has a better control effect.

1. Introduction

As a digitally controlled servo motor, after matching the corresponding motor drive circuit, the stepper motor changes the excitation state of the motor through the electric pulse signal to make the rotor to rotate. There is a corresponding synchronous corresponding relationship between the input pulse and the motor displacement, and the change in the motor speed is mainly controlled by the pulse input frequency. Therefore, stepper motors have the advantages of high positioning accuracy, no position cumulative error, fast response speed, high reliability, convenient control and so on. They are widely used in commercial and industrial applications such as robotic systems, CNC machines, printers, and domestic appliances [1]. On the one hand, using the open-loop control method to control the position of the stepper motor is relatively simple, but the accuracy is low [2]. On the other hand, using the closed-loop control method to control the position of the stepper motor has high precision and can control the position of the stepper motor more efficiently and stably, which is of great significance to promote the further application of the stepper motor.

Stepper motor open-loop drive control is a low-cost and simple control mode because open-loop control does not require additional position sensors. However, when the load torque of the motor changes, a very serious problem in the open-loop control mode is the out-of-step problem, especially in the case of high speed, even the small torque disturbance will appear this kind of problem [3].

In reference [4]-[5], several control methods using subdivision or subdivision combined with closed-loop control are provided a detailed description. These control methods can improve the control performance of the stepper motor. However, these control methods can not solve the problem of torque fluctuation of stepper motor very well. In order to further improve the control performance of stepper motor, on the basis of motor vector control, combined with a variety of damping algorithms of nonlinear control, Such as Kalman filter, adaptive approximation, sliding mode control technology, model-based control, Jacobian linearization observer, harmonic injection mode, optimal control [6]-[11] and so on. It can effectively eliminate the torque ripple caused by the nonlinear characteristics of the stepper motor.

In the closed-loop control mode of the stepper motor, controlling the current in the coil of the motor is the heart of the control in stepper motor drives. Various effective control schemes, such as conventional proportional-integral (PI) control [12], intelligent control [13] and fuzzy control [14], are detailed in the literature. However, in these schemes, the current controller coefficient is only determined according to the motor parameters, or the calculation is more complex. To adapt to the change of motor parameters and running speed, based on the traditional PI algorithm, the current algorithm is improved to improve the working bandwidth of the stepper motor.

In this paper, the two-phase hybrid stepper motor is taken as the research object, the coefficient of PI current controller is calculated with the help of motor parameters and motor speed, and the sliding mode variable structure control mode is adopted, which is combined with the improved PI current controller. The simulation model of the stepper motor position closed-loop control system is established, and angle control of the stepper motor in a given position is verified by simulation.

2. Mathematical model of stepper motor

Because the stepper motor is a highly nonlinear device, a series of assumptions and simplification are carried out: the saturation phenomenon of the magnetic circuit of the motor is ignored, and the controlled object is treated as a linear element, the stator end and interpole magnetic flux leakage are ignored, and the magnetic flux leakage at the end of the stator and between the poles is ignored [15].

In the case of the above assumption, the two-phase voltage equation of the two-phase hybrid stepper motor is obtained as shown in formula (1)

$$\begin{cases} U_{\mathrm{A}} = r_{\mathrm{A}} i_{\mathrm{A}} + \left(L_0 - L_2 \cos 2\theta\right) \dfrac{di_{\mathrm{A}}}{dt} - L_2 \sin 2\theta \dfrac{di_{\mathrm{B}}}{dt} + 2\omega_{\mathrm{e}} L_2 \left(i_{\mathrm{A}} \sin 2\theta - i_{\mathrm{B}} \cos 2\theta\right) - k_{\mathrm{e}} \omega_{\mathrm{r}} \sin\theta \\ U_{\mathrm{B}} = r_{\mathrm{B}} i_{\mathrm{B}} + \left(L_0 + L_2 \cos 2\theta\right) \dfrac{di_{\mathrm{B}}}{dt} - L_2 \sin 2\theta \dfrac{di_{\mathrm{A}}}{dt} - 2\omega_{\mathrm{e}} L_2 \left(i_{\mathrm{B}} \sin 2\theta + i_{\mathrm{A}} \cos 2\theta\right) + k_{\mathrm{e}} \omega_{\mathrm{r}} \cos\theta \end{cases} \tag{1}$$

In the formula, U_{A}、U_{B}、i_{A}、i_{B}、r_{A}、r_{B} are the phase voltage, phase current and phase resistance of A and B phase windings, ω_{r} is the mechanical angular velocity of the rotor, k_{e} is the back EMF coefficient and θ is the rotor angle.

The mechanical motion equation of the two-phase hybrid stepper motor is shown in formula (2)

$$T_{\mathrm{e}} = J \frac{\mathrm{d}\omega_{\mathrm{r}}}{\mathrm{d}t} + \mathrm{B}\omega_{\mathrm{r}} + T_{\mathrm{L}} \tag{2}$$

In this formula, T_{e} is the electromagnetic torque, J is the moment of inertia, B is the viscosity coefficient, T_{L} is the load torque.

3. Mathematical model in the rotating coordinate system

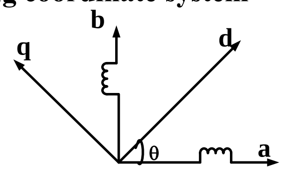

Figure 1. Vector diagram of two-phase hybrid stepper motor

The electromagnetic torque equation of the motor in the rotating coordinate system is:

$$T = N_{\mathrm{r}} \left(L_{\mathrm{d}} - L_{\mathrm{q}}\right) i_{\mathrm{d}} i_{\mathrm{q}} + N_{\mathrm{r}} i_{\mathrm{q}} M_{\mathrm{sr}} I_{\mathrm{m}} \tag{3}$$

In formula (3), N_{r} is the rotor teeth number, M_{sr} is the maximum of mutual inductance between stator and rotor, I_{m} is an equivalent excitation current when the permanent magnet is equivalent to an exciting winding. In the vector control mode of field orientation, to facilitate the control, the control mode is i_{d}=0 generally adopted. According to the above formula, when the control mode is i_{d}=0 adopted, the torque equation is shown in formula (4)

$$T = N_{\mathrm{r}} i_{\mathrm{q}} M_{\mathrm{sr}} I_{\mathrm{m}} \tag{4}$$

From the above formula, it can be seen that the output torque of the two-phase hybrid stepper motor is linearly related to the actual i_q , and the magnitude of the load determines the i_q of the motor.

4. Sliding mode control design

Through the previous analysis of the stepper motor formula (2) and formula (4) can be obtained:

$$\dot{\omega} = -B\omega/J + T_e / J - T_L / J = a\omega + bi_q + dT_L \tag{5}$$

In formula (5), $a = -B / J, b = \left(N_r I_m M_{sr}\right) / J, d = -1 / J$

4.1 Select the sliding surface

There are three kinds of sliding surfaces: linear sliding surface, nonlinear sliding surface, and time-varying sliding surface. The sliding mode control with a linear sliding mode surface can not make the state tracking error converge to zero in the effective time, and when there is a certain external disturbance, it may bring a large steady-state error and can not meet the required performance index. Although the time-varying sliding mode surface can well weaken the chattering, it is more complex in the implementation of the algorithm. In this paper, choose nonlinear sliding surface

$$s = c_0 \int edt + c_1 e + \dot{e} \tag{6}$$

The addition of the position error integral term can greatly reduce the steady-state position error of the system and improve the tracking performance of the system.

Hypothetical:$e=\theta_r-\theta$, $x_1=e$, $x_2=\dot{x}_1$, $u=i_q$, θ_r is assumed that the position given, θ is the actual position of the stepper motor and ω is the actual speed of the stepper motor. The state equation of position error of the stepper motor is obtained as follows.

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = \ddot{e} = \ddot{\theta}_r - a\omega - bu - dT_L \end{cases} \tag{7}$$

Choice index approach law:

$$\dot{s} = -\varepsilon \operatorname{sgn}(s) - ks \quad \varepsilon > 0, k > 0 \tag{8}$$

4.2 Get the control law

In conjunction with the above formula, the control rate can be obtained:

$$u = \left(c_0 e + c_1 \dot{e} + \ddot{\theta}_r - a\omega\right)/b + \left(\varepsilon \operatorname{sgn}(s) + ks - dT_L\right) / b \tag{9}$$

4.3 Stability Verification

For the above sliding mode controller, select the Lyapunov function $V = s^2 / 2$

By the generalized sliding mode condition:

$$\dot{V} = s\dot{s} = s\left[-\varepsilon \operatorname{sgn}(s) - ks\right] = -\varepsilon |s| - ks^2 \tag{10}$$

As long as $\varepsilon > 0$ and $k > 0$, $s\dot{s} < 0$ is true.

Thus it can be seen that the sliding mode surface is stable and satisfies the reachability condition, that is, the generalized sliding mode condition is satisfied.

Based on the above analysis of the sliding mode control mode of the stepper motor position control, the related simulation of the stepper motor sliding mode control is shown in figure 2:

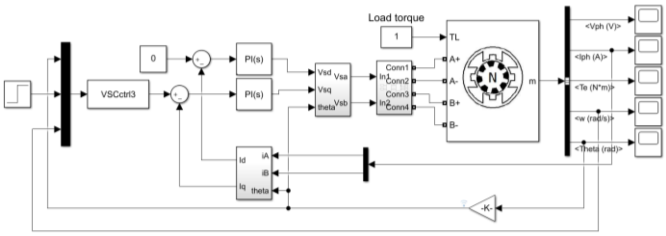

Figure 2. Simulation model of sliding mode control for stepper motor

5. Currently closed-loop design

In the design of the stepper motor current controller, the voltage equation in formula (1) is considered, and an improved PI current controller is proposed as.

$$PI(s) = K_s\left(K_p + \frac{K_i}{s}\right)$$

Compared to the conventional PI control algorithm, the improved PI current controller has one more gain called the speed compensation gain K_s. In this study, both K_p and K_i depend on the motor parameters (R and L), whereas the gain K_s is determined by motor speed. Therefore, the improved PI current controller can adapt to the changes of motor parameters and speed.

For the standard second-order system with damping ratio ξ and natural frequency ω_0, the coefficients of the improved PI current controller as

$$K_p = \frac{2\xi\omega_0 L - R}{K_s} \quad \text{and} \quad K_i = \frac{\omega_0^2 L}{K_s}$$

It should be noted that ω_0 determines the bandwidth of the current loop. On the one hand, for the stepper motor with vector control, the running speed of the motor is directly related to the frequency of the reference current. Therefore, to expand the working bandwidth of the motor, it is necessary to increase the bandwidth of the current loop. The gain K_s varies with the speed of the stepper motor to maintain the current performance. Here, the value of K_s is defined as:

$$K_s = \frac{1}{5}\omega + 1$$

Based on the above analysis of the new PI control current loop, the simulation of the sliding mode control of the progressive motor is shown in figure 3:

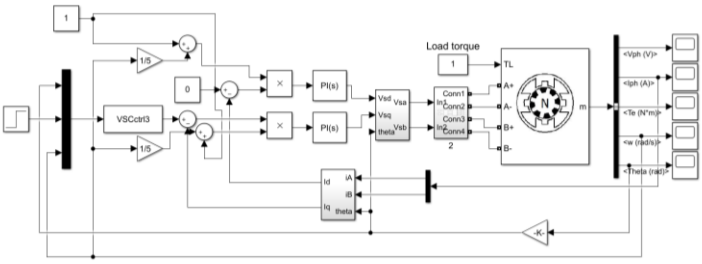

Figure 3. Improved simulation model of sliding mode control for stepper motor

6. Simulation analysis and comparison

To verify the control effect of the improved current closed-loop sliding mode control in the position control system of the two-phase hybrid stepper motor, the control effect of the improved current closed-loop sliding mode control is compared with that of the unimproved sliding mode control. The simulation verification of the control system is carried out by using MATLAB/Simulink software so that the system tracks the abrupt position signal. The parameters of the two-phase hybrid stepper motor used in the simulation are shown in table 1.

Table 1. Parameters of two-phase hybrid stepper motor

Parameter	value
Step angle /°	1.8
Rated current /A	3
Phase inductor /mH	6.8
Phase resistance /Ω	1.55
Moment of inertia /g·cm^2	670
Hold torque /N·m	2.8

The abrupt position signal is suddenly given a 10 °signal at 0.05s, and the two-phase hybrid stepper motor starts directly with the load torque of 1Nm. The resulting position response curve is shown in figure 4.

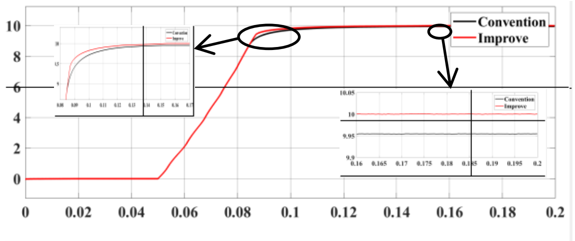

Figure 4. Comparison of convention and improved position response

It can be seen from figure 4 that after the control system is improved. The reaction speed is faster and the time to reach the target angle is shortened, which shows that the improved algorithm has faster response and higher accuracy in the control system.

7. Conclusion

Based on the electrical and mechanical characteristics of the two-phase hybrid stepper motor, a new PI current controller is designed by using sliding mode control, which expands the working bandwidth of the stepper motor and the bandwidth of the current loop. To improve the control accuracy and operational stability of the stepper motor, the improved current controller is simulated and compared with the convention current controller. The simulation results show that the improved method can get faster response and higher control accuracy, which show the feasibility of this design. At the same time, because of its simple implementation, it is also of great significance in practical application.

References

[1] S. Derammelaere et al., "The efficiency of hybrid stepping motors: Analyzing the impact of control algorithms," IEEE Ind. Appl. Magaz., Jul./Aug.2014.

[2] Dong Lei, Yang Xiangyu, Zhao Shiwei. Research on position Control of two-Phase Hybrid stepping Motor based on sliding Mode algorithm [J]. Micromotor, 2015,48 (09): 49-53.

[3] Kien Minh Le, Hung Van Hoang, and Jae Wook Jeon, "An Advanced Closed-Loop Control to Improve the Performance of Hybrid Stepper Motors" IEEE Transactions on Power Electronics, Sep 2017

[4] Y. Lee, D. Shin, W. Kim, and C. C. Chung, "Proximate in-phase current estimator to reduce torque ripple in permanent-magnet stepping motor," IEEE Trans. Ind. Electron., Mar. 2016.

[5] S. M. Yang and E. L. Kuo, "Damping a hybrid stepping motor with estimated position and velocity," IEEE Trans. Power Electron., vol. 18, no. 3, pp. 880–887, May 2003.

[6] P. Crnosija, B. Kuzmanovic, and S. Ajdukovic, "Microcomputer implementation of optimal algorithms for closed-loop control of hybrid stepper motor drives," IEEE Trans. Ind. Electron., Dec. 2000.

[7] J. Hirai, T. W. Kim, and A. Kawamura, "Position-sensorless drive of linear pulse motor for suppressing transient vibration," IEEE Trans. Ind. Electron., Apr. 2000.

[8] W. D. Chen, K. L. Yung, and K. W. Cheng, "Profile tracking performance of a low ripple hybrid stepping motor servo drive," IEE Proc. Control Theory Appl., Jan. 2003.

[9] K. W. Tsui, N. C. Cheung, and K. C. Yuen, "Novel modeling and damping technique for hybrid stepper motor," IEEE Trans. Ind. Electron., Jan. 2009.

[10] T. S. Hwang, J. K. Seok, and D. H. Kim, "Active damping control of linear hybrid stepping motor for cogging force compensation," IEEE Trans. Magn., Feb. 2006.

[11] S. M. Yang, F. C. Lin, and M. T. Chen, "Micro-stepping control of a two-phase linear stepping motor with three-phase VSI inverter for high-speed applications," IEEE Trans. Ind. Appl., Sep./Oct. 2004.

[12] Y. I. Son, I. H. Kim, D. S. Choi, and H. Shim, "Robust cascade control of electric motor drives using dual reduced-order PI observer," IEEE Trans. Ind. Electron., Jun. 2015.

[13] M. Marufuzzaman, M. B. I. Reaz, and M. A. M. Ali, "FPGA implementation of an intelligent current DQ PI controller for FOC PMSM drive," in Proc. IEEE Comput. Appl. Ind. Electron., 2010.
[14] J. W. Jung, Y. S. Choi, V. Q. Leu, and H. H. Choi, "Fuzzy PI-type current controllers for permanent magnet synchronous motors," IET Electr. Power Appl., 2011.
[15]. Sakamoto Application Technology of stepping Motor [M]. Science Press, (Japan), 2010