Research on Control Algorithm of Electric Linear Loading System

Jianjie Lei¹, Yuanxun Fan¹, Weidong Pan¹, Dejia Tang², Jian Tao² and Zhiwei Xu²

¹School of Mechanical and Electrical Engineering, Nanjing University of Science and Technology, NanJing, China
²Shanghai Aerospace Control Technology Institute, Shanghai, China

Abstract. The electromagnetic loading system is widely used in the test system of aircraft, and its loading force and accuracy are the basis for many tests. Therefore, the study of loading system is an important research content. This paper focuses on the problem of low loading accuracy in the use of the linear loading system, and proposes a control algorithm based on fuzzy PID and repetitive control. The control algorithm effectively suppresses the impact of nonlinear factors such as mechanical friction, gaps and the loading form of rotating motor with ball screw, but the difficulty and high cost of linear motor, this paper adopts the rotary servomotors with the electric machines, and the ELLS is mainly divided into the linear servomotors, the rotary servomotors and the hybrid servomotors. The simulation results show that the control algorithm is feasible, which has a certain engineering reference value.

1 Introduction

At present, most of the research on the linear loading system is to improve the loading accuracy. The factors such as mechanical friction, gaps and the loading form of rotating motor with ball screw, but the difficulty and high cost of linear motor, this paper adopts the rotary servomotors with the electric machines, and the ELLS is mainly divided into the linear servomotors, the rotary servomotors and the hybrid servomotors. As shown in Fig.1, the host computer PC sends a sine signal to the motor controller, sensor, multi-channel data acquisition system and other system devices through the EtherCAT communication protocol to control the output torque of the motor. The motor controller and the motor are the core components of the system. The motor controller sends the motor current command to the motor to drive the motor, and the motor drives the load device to achieve the purpose of loading. The load motor converts the rotational force into a linear force by the ball screw. Considering the shortcomings in control accuracy and high-precision control performance is the core issue of the system, how to improve the system's high response and tracking performance and significantly restrain the extra torque and improve the stability of the system. The repetitive controller periodically adjusts the deviation, which reduces the system's overshoot and enhances in tracking control interference ability of the system, but the self-adaptive anti-jamming ability of the system, but the self-adaptive anti-jamming ability of the system, and nearly eliminates the load dependence of the system. R Ghazali[6] adopts a robust controller and the repetitive controller. It not only improves the performance of ELLS. Ni[2] proposed a method based on fuzzy reasoning and neural network to suppress the extra force and improve the loading accuracy. The simulation results show that the composite control algorithm based on fuzzy PID and repetitive control can significantly reduce the extra force and improve the loading accuracy.

2 System structure

The successful development of ELLS can not only shorten the development cycle of the tested mechanism, but also improve test reliability and success rate. At present, most of the test device used to test the performance of linear servo is the hydraulic system. The shortcomings of hydraulic system are: high maintenance cost, long development cycle, low repeatability, and test environment requirements. Electric Linear Loading System (ELLS) is an important trend of the test device used to test the performance of linear servo. As shown in Fig.2, the host computer PC sends a reference signal to the motor controller, sensor, multi-channel data acquisition system and other system devices through the EtherCAT communication protocol to control the output torque of the motor. The motor controller and the motor are the core components of the system. The motor controller sends the motor current command to the motor to drive the motor, and the motor drives the load device to achieve the purpose of loading. The load motor converts the rotational force into a linear force by the ball screw. Considering the shortcomings in control accuracy and high-precision control performance is the core issue of the system, how to improve the system's high response and tracking performance and significantly restrain the extra torque and improve the stability of the system. The repetitive controller periodically adjusts the deviation, which reduces the system's overshoot and enhances in tracking control interference ability of the system, but the self-adaptive anti-jamming ability of the system, and nearly eliminates the load dependence of the system. R Ghazali[6] adopts a robust controller and the repetitive controller. It not only improves the performance of ELLS. Ni[2] proposed a method based on fuzzy reasoning and neural network to suppress the extra force and improve the loading accuracy. The simulation results show that the composite control algorithm based on fuzzy PID and repetitive control can significantly reduce the extra force and improve the loading accuracy.
3 System mathematical model

3.1 Load motor model

\[ T_e = J_e \frac{d^2 \theta_e}{dt^2} \]

\[ T_L = J_L \frac{d^2 \theta_L}{dt^2} \]

\[ T_B = J_B \frac{d^2 \theta_B}{dt^2} \]

\[ \theta_L = \theta_e + \theta_B \]

3.2 Intermediate transformation model

\[ \theta_m = \text{motor angular displacement} \]

\[ \theta_L = \text{load angular displacement} \]

\[ \theta_B = \text{ball screw angular displacement} \]

3.3 Torque and force relationship of ball screw

\[ F = \frac{T_s}{r} \]

\[ F = \frac{2 \pi L}{P} \]

4 Composite controller designer

4.1 Current loop design
**4.2 Force controller design**

The input and output variables are selected according to the current loop control. It can be seen from the frequency characteristics of the current loop in Fig.3 that the phase lag and amplitude are small.

**4.2.1 Fuzzy PID Controller Design**

The closed-loop transfer function consists of a first-order lag function of the system as shown in (8), the current open loop transfer function is:

\[ G(s) = G(s) (L(s)) \]

When the ELLS is in normal operation, the error \( e \) becomes stable, the system is a stable system whose static deviation is commonly used to evaluate the stability of the control system. That is, the closer to 0 the closed-loop gain is, the smaller the static deviation is. From (9), when the phase margin is 0, the closed-loop phase shift is 90°, it is a stable system whose phase margin is small.

The closed-loop phase shift of a stable system is close to 0, the closed-loop phase margin should be greater. To avoid the effect of the proportional gain is far greater than the derivative gain, the proportional coefficient of the closed-loop transfer function is as follows:

\[ K_p = \frac{i_q}{S + R_s} + G_q \]

\[ G_q = \frac{i_q}{S + R_s} + G_q \]

\[ G(s) = G(s) (L(s)) \]

When the ELLS starts or stops running, the error \( e \) is large, so as to speed up the response of the system, the proportional gain is close to 0 and the static deviation of the system is small.

Because the proportional gain is far greater than the derivative gain, the gain is close to 0 and the static deviation of the system is small.

\[ G(s) = G(s) (L(s)) \]

Considering the problems of large load steady-state error, the current loop controller can be designed as follows:

\[ K_p = \Delta K_p \]

\[ K_i = \Delta K_i \]

\[ K_d = \Delta K_d \]

The above (7) is the proportional coefficient of the closed-loop transfer function, the gain is close to 0 and the static deviation of the system is small. The specific formula is as shown in (8), the current loop closed loop frequency diagram of the system is shown in Fig.5.

**Figure 3**

Current loop control block diagram.

**Figure 4**

Bode diagram of the system.

**Figure 5**

Current loop closed loop frequency diagram.
The repetitive control is based on the internal model to get the actual control volume. When ELLS outputs a constant force, e and ec should be small at this moment. In order to make the repetitive controller design appropriately, feedback control, and takes each coefficient of the membership function of the fuzzy rules of the system, the repetitive amplitude attenuation and phase compensation are completed. In this way, system stable, the rate of change of error e are medium-sized, and the interference signal is:

\[ e(S) = Q(S)e(S) \]

According to the stability criterion of classical control theory, all the eigenvalues of the system are in the left half plane, so the design should meet the (16):

\[ T(s) | 1 - Q(S)e 0 \]

From (14), we get the system's characteristic equation

\[ \frac{G(S)}{C(S)}P(S) | 1 - Q(S)e 0 \]

From (13), we can see that when \( K = 1 \), the tracking capability is good, the steady-state error of the load [10]. The selection of the membership function of the fuzzy controller is shown below.

\[ K = \frac{1}{\sum_{i=1}^{N} \mu_{i}(x)} \]

4.2.2 Repetitive controller design

The (13) can be transformed into:

\[ G(S)P(S) = \frac{T(S)e(S)}{1 - Q(S)e 0} \]

So the system is stable.

\[ T(S) = \frac{G(S)P(S)}{1 - Q(S)e 0} \]

In (15), \( S = \frac{1 + G(S)}{\frac{1}{e}G(S)} \), so the system is stable.

\[ T(S) = \frac{G(S)P(S)}{1 - Q(S)e 0} \]

From (13), \( G(S)P(S) = \frac{T(S)e(S)}{1 - Q(S)e 0} \) and the interference signal is:

\[ Q(S)e 0 \]

\[ G(S)P(S) = \frac{T(S)e(S)}{1 - Q(S)e 0} \]

\[ T(S) = \frac{G(S)P(S)}{1 - Q(S)e 0} \]

\[ G(S)P(S) = \frac{T(S)e(S)}{1 - Q(S)e 0} \]

\[ T(S) = \frac{G(S)P(S)}{1 - Q(S)e 0} \]

\[ T(S) = \frac{G(S)P(S)}{1 - Q(S)e 0} \]

\[ T(S) = \frac{G(S)P(S)}{1 - Q(S)e 0} \]

\[ T(S) = \frac{G(S)P(S)}{1 - Q(S)e 0} \]

\[ T(S) = \frac{G(S)P(S)}{1 - Q(S)e 0} \]
Figure 8.

5 System simulation

Table 1. System parameters

| Parameter  | Value |
|------------|-------|
| $K_s$      | $\frac{V}{Kpm}$ |
| $J_s$      | $\frac{Kgm}{rad/s}$ |
| $B_s$      | $\frac{Nm \cdot rad}{s}$ |
| $K_m$      | $\frac{Nm \cdot m}{A}$ |
| $J_m$      | $\frac{Kgm}{rad/s}$ |
| $B_m$      | $\frac{Nm \cdot m}{A}$ |
| $P_e$      | $\frac{Nm}{mm}$ |

5.1 Linear load force tracking performance

5.2 Excess force suppression ability
The actuator follows the specified sinusoidal path acted as the disturbance input. In order to compare the control effects under different controllers, traditional PID control and redundant force suppression simulation under compound control are carried out. Fig. 1 shows that when the steering gear moves at 1mm/1Hz, the composite control compared with traditional PID extra force reduces from 150N to 60N. Fig. 13 shows that when the steering gear moves at 1mm/3Hz, the composite control reduces 380N to 110N compared with the traditional PID, and as time goes by, the effect of restrain force is getting better and better.

6 Conclusion

ELLS is a key part in the design of electric load simulator. Compared with the torque servo system, ELLS has strong coupling and many nonlinear factors. In this paper, a two-loop control structure of current loop and force loop closed-loop feedback. Current loop is controlled by Proportional control, which improves the current response and steady-state error. The force loop uses the parallel method of fuzzy PID and repetitive control, which not only improves the accuracy of the loading force, but also reduces the steady-state error. The simulation shows that the control method is very good at tracking servo capability and suppressing excess force in low frequency.

References

1. Wang Chao, Hou Yuanlong, Wang Li, Influence analysis on electric load simulator for the gun control system. Electric Machines and Control, 2015, 20(12): 73-81.
2. Ni Zhisheng, Wang Mingyan. A novel method for restraining the redundancy torque based on DFNN, Journal of harbin institute of technology, 2012, 44(10):79-84.
3. Wang Chengwen, Jiao Zongxia, Wu Shun, etc. A practical nonlinear robust control approach of electro-hydraulic load simulator[J]. Chinese Journal of Aeronautics, 2014, 27(3):735-744.
4. Wang Xingjian ,Wang Shaoping ,Zhao Pan. Adaptive Fuzzy Torque Control of Passive Torque Servo Systems Based on Theorem and Input-to-state Stability. Chinese Journal of Aeronautics, 2012, 25(12):906-916.
5. ND Manring ,L Muhi, RC Fales ,etc. Using Feedback Linearization to Improve the Tracking Performance of a Linear Hydraulic-Actuator[J]. The American society of mechanical engineers, 2018, 1(20): 1-6.
6. R. Ghazali, Y. M. Sam, M. F. Rahmat, etc. Discrete Sliding Mode Control for a Non-minimum Phase Electro-hydraulic Actuator System. Asian Control Conference (ASCC), 2015:1-6.
7. Truong DQ, Ahn KK. Force control for hydraulic load simulator using self-tuning grey predictor-fuzzy PID. Mechatronics, 2009, 19(2):233-248.
8. Wang C W,Jiao Z X,Luo C J. An improved velocity synchronization control on electro-hydraulic load simulator. Acta Aeronautica et Astronautica Sinica, 2012, 33(9): 1717-1725.
9. X.J.Wang, S.P.Wang,and X.D.Wang, Electrical Load Simulator Based On Velocity-Loop Compensation And Improved Fuzzy-PID , International Symposium on Industrial Electronics, 2009.
10. E Tung ,G Anwar ,M Tomizuka..Low Velocity Friction Compensation and Feedforward Solution based on Repetitive Control. American Control Conference (ASCC). 2009, 115(2): 2615-2620.