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Research on improved control method of electromechanical actuation

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Abstract: This study presents a kind of feedback between smooth and discontinuous feedback control method for electromechanical servo system. First, the construction and working principle of electromechanical servo systems was introduced on the basis of their structure characteristic. Then with the building of the electromechanical servo system structure, some research on the control strategy of permanent-magnet synchronous motors has been developed control in the light of their control characteristics. Combined with the theory of the field oriented control and the structure features and performance metrics of the mechanical and electrical servo system, a simulation model for the mechanical and electrical servo system was built. The simulation result shows the reliability of this method.

1 Introduction

In recent years, power-by-wire (PBW) actuation system is the main topic in aircraft control [1, 2]. Many scholars have found two new actuation technologies that can replace hydraulic actuation, which are electro-hydraulic actuation (EHA) and electromechanical actuation (EMA). One of the advantages of PBW actuation system is that it can eliminate the hydraulic lines throughout the aircraft, so the distribution weight for the system will be strictly reduced. However, the EHA system consists of a self-contained hydraulic system driven by an electric motor pump, so the EHA is more weight than a hydraulic actuator.

The EMA is driven by a permanent magnet synchronous motor (PMSM) servo system. So the PMSM servo system is the core of the EMA. As the typical vector control theory is put forward and mature, the development of AC servo drive technology is greatly promoted. The simplified mathematical model of AC motor is equivalent to the mathematical model of DC motor excitation. It is hard to achieve independent control of motor torque and field by, respectively, controlling the d-axis and q-axis current.

Based on the model of the electromechanical actuator and the analysis of control strategy, a proportional–integral–derivative (PID) control method with feedforward and a non-smooth control were proposed. Finally, high precision servo control of electromechanical actuator was realised by simulation.

2 Structural principle of EMA

There are two common structural forms in EMA. One of the schemes is the re-entry electromechanical actuators, as shown in Fig. 1. When the servo motor rotates, the screw rod or the nut is driven to rotate by a gear reducer or a synchronous belt, and the nut or the screw rod translates the rotational motion into linear motion through the linear limiting mechanism. However, there are obvious drawbacks in the scheme. The existence of gear reducer or synchronous belt and the transmission gap between the servo motor and the lead screw makes the position control strategy more complex of the servo system.

Another one type removes the reducer, so servo motor and the screw nut system were connected directly, as shown in Fig. 2.

When the motor rotates, the screw or nut is directly driven to rotate, and the nut or the screw rod translates the rotational motion into linear motion through the linear limiting mechanism. The servo motor and the screw nut system can be integrated into the design to acquire a high weight ratio. So the direct drive type EMA can achieve lighter weight.

A certain type of EMA is used as the background to determine the relevant parameters of each component in this paper, the indicators are as follows:

- Output force: 4.5 kN
- Speed: 125 mm/s
- Displacement stroke: 120 mm

The electromechanical servo system is shown in Fig. 3. According to the servo position command, the control system realises the adjustment of getting the electromechanical actuator servo motor corner position, speed and torque. The electromechanical actuator mainly receives the power signal transmitted by the servo system, and transfers the rotor angle, and drives the screw to transform the rotation motion of the servo motor into linear motion. This paper does not consider the reducers.

3 Feedforward compensation PID control method

In the electromechanical servo system application, the position controller is usually designed as proportional. By adjusting the size of the proportional gain, the position response of servo system can have no overshoot, but this usually reduces the response speed of the system. In order to make the electromechanical servo system with higher positioning accuracy, generally, the upper controller should complete the error accumulation of the given position and the actual position, and a compensation algorithm is needed, and proportional adjustment of the position loop does not achieve ideal response speed.

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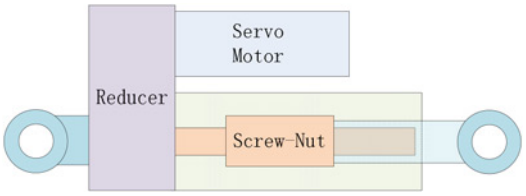


Fig. 1 *Re-entry type EMA*

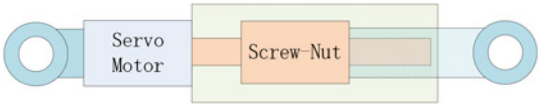


Fig. 2 *Direct drive type EMA*

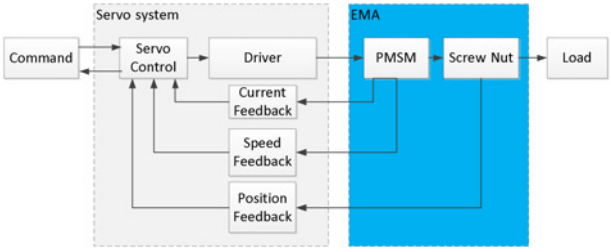


Fig. 3 *Overall framework of the electromechanical servo system*

Feedforward control is usually used to suppress the disturbances of servo system and enhance the robustness of the system. In the application of the output signal to track the input signal directly, the closed-loop servo system usually leads to the tracking delay, and the feedforward can increase the tracking speed of the servo system.

3.1 Feedforward compensation model

In the electromechanical servo system with high accuracy and high response, the feedforward compensation controller can be used to improve the position tracking performance of the servo system. The feedforward controller is one of the digital filters, belonging to the finite impulse response filter.

In the classical control theory, the feedforward compensation control is realised based on the idea of compound control. When the closed-loop system is a continuous system, the transfer function product of the current feed compensation link and the closed loop system is 1, the output can be completely reproduced. Feedforward compensation is designed for PID control to improve the tracking performance of the system [3]. Fig. 4 shows the control structure of PID with feedforward compensation.

The feedforward compensation model is designed as

$$u_f(s) = y_d(s)\frac{1}{G(s)} \tag{1}$$

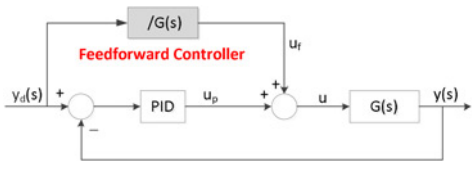


Fig. 4 *Control structure of PID with feedforward compensation*

The total output is the sum of PID control output and feedforward control output

$$u(t) = u_p(t) + u_f(t) \tag{2}$$

The discrete form is written as

$$u(k) = u_p(k) + u_f(k) \tag{3}$$

There are few papers about electromechanical servo system based on feedforward compensation PID. According to the theory and practical experience, the feedforward compensation of speed loop and current loop is introduced to the three-loop control system of current loop, speed loop and position loop.

The realisation of fast positioning and high precision following of electromechanical servo system is essentially the fast response and tracking of the instruction signal. Feedforward control can demodulate the instructions and transmit them directly as compensation for the system response. In the feedforward compensation control, it is necessary to ensure the stability of the speed loop and the current loop first.

3.2 Simulation results

Simulation condition: 4 Hz sinusoidal reference command, amplitude 3.5 mm, simulation time 2 s, without load. The response curve performance is generally good, so about 10% of the minor load, set to 500 N.

Fig. 5 shows the response curve and the details without feedforward compensation. Fig. 6 shows the response curve and the details of feedforward compensation. It can be seen from Figs. 5 and 6 that the system respond slowly without feedforward compensation.

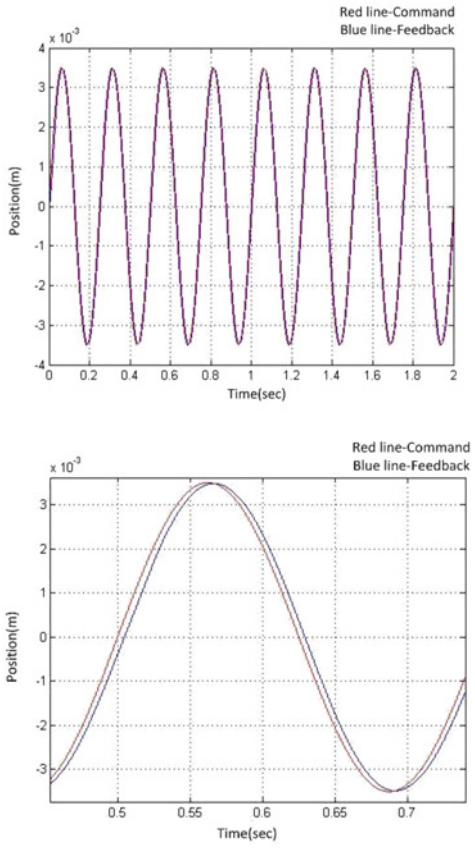


Fig. 5 *Response curve and the big picture without feedforward compensation*

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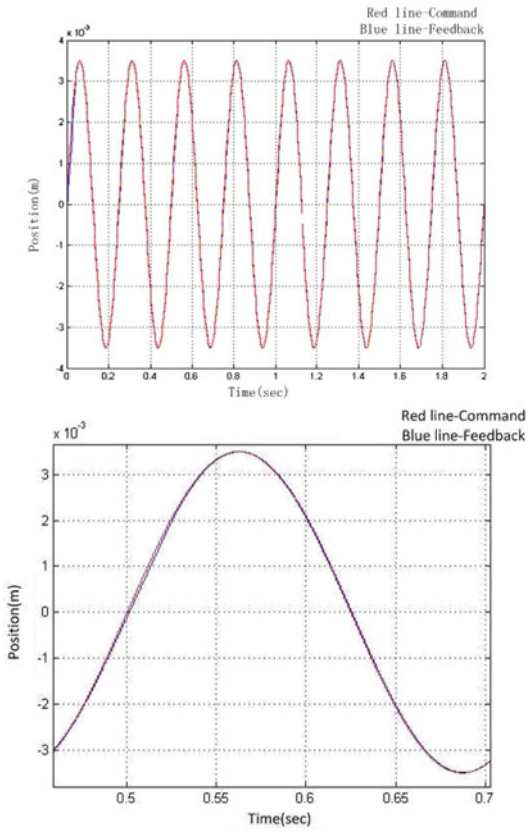


Fig. 6 *Response curve and the big picture with feedforward compensation*

The following response error without feedforward compensation is shown in Fig. 7. The following response error with feedforward compensation is shown in Fig. 8. It can be seen that the following response error without feedforward compensation is greater than the feedforward compensation system. The feedforward control in the electromechanical system can improve the system control performance.

4 Between smooth and discontinuous feedback control method

Non-smooth control is a non-linear control method to make a balance between discontinuous control and smooth control. In theory, the study will compensate for the gap between the discontinuous control and the smooth control, and it also can improve

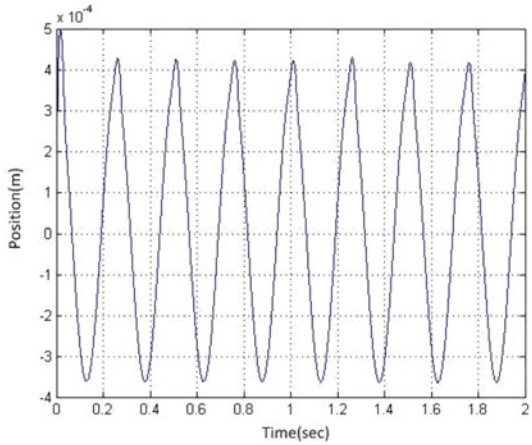


Fig. 7 *Sinusoidal tracking error without feedforward compensation*

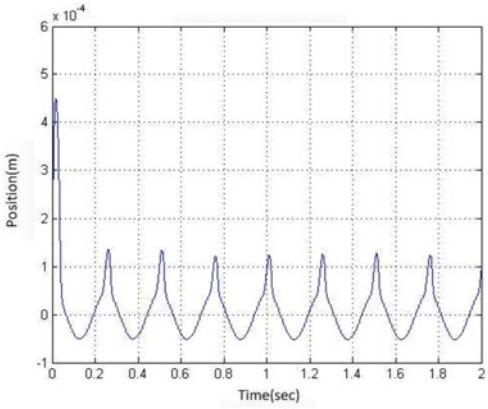


Fig. 8 *Sinusoidal tracking error with feedforward compensation*

the non-linear system control theory. From the application point of view, the advantages of this method are such as strong disturbance resistance and rapid convergence, potential development. The electromechanical servo system has a high demand for system response and tracking accuracy, so it needs fast convergence and strong anti-disturbance performance.

4.1 Non-smooth state feedback control

In the design of the control system, the convergence is the key. According to the research results in the literature, it shows that in most design methods of the control system, the exponential form is the fastest convergence rate, and cannot get better convergence performance. The reason is that the closed-loop system which satisfies Lipschitz continuity condition is discussed.

These synthesis methods and control analysis belong to infinite time stability and control problems [4–6]. From the point of view of time optimisation of control system, the method of closed-loop finite-time convergence control (non-smooth control method) is a time-optimal control method [7–9]. Second, there are always disturbances in the actual system. In the presence of disturbances, the literature studies show that, even if the system is perturbed, the non-smooth control system has better disturbance rejection performance [10, 11].

In addition, under normal circumstances, there are non-smooth state feedback controller when the system can be stabilised by smooth state feedback, and some systems, which cannot be stabilised by smooth state feedback, may be stabilised by the non-smooth state feedback, namely the non-smooth smooth control has wider application than the general control method [12–14].

The non-smooth control system has fast convergence performance near the equilibrium point, because of the fractional power function, compared with smooth controller, non-smooth controller has larger amplitude control near the equilibrium point, and it ensures that the control system has faster convergence [15, 16].

Take the first-order system as an example

$$\dot{x} = u \tag{4}$$

The non-smooth controller is designed as

$$u = -k\text{sign}(x)|x|^{\alpha}, \quad 0 < \alpha < 1, \quad k > 0, \tag{5}$$

The smooth controller is designed as

$$u = -kx, \quad k > 0 \tag{6}$$

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Substituting the controller (5) into system (4), the closed-loop system is as follows:

$$\dot{x} = -k\text{sign}(x)|x|^{\alpha} \tag{7}$$

After integration, the solution of system (7) can be obtained

$$x(t) = \begin{cases} \text{sign}(x(0))\left(|x(0)|^{1-\alpha} - k(1-\alpha)t\right)^{1/(1-\alpha)}, & 0 < t \le \dfrac{|x(0)|^{1-\alpha}}{(1-\alpha)k} \\ 0, & t > \dfrac{|x(0)|^{1-\alpha}}{(1-\alpha)k} \end{cases} \tag{8}$$

Similarly, substituting the controller (6) into the system (4), the closed-loop system is as follows:

$$\dot{x} = -kx \tag{9}$$

the solution of system (9) can be obtained

$$x(t) = \mathrm{e}^{-kt}x(0) \tag{10}$$

From the analysis, it can be seen that the non-smooth system (7) is obviously faster than the asymptotically stable system (9).

Take the double integral system as an example

$$\dot{x}_1 = x_2, \quad \dot{x}_2 = u + d(t) \tag{11}$$

where x is the state variable, u is the input of control and D is bounded disturbance. When the system (9) does not consider the disturbance, which means $d=0$, the controller with the global finite time is given by using the theory of homogeneity

$$u = -k_1\text{sign}(x_1)|x_1|^{\alpha 1} - k_2\text{sign}(x_2)|x_2|^{\alpha 2} \tag{12}$$

where $k_1>0$, $k_2>0$, $0<\alpha_1<1$, $\alpha_2=2\alpha_1/(1+\alpha_1)$.

The position PID controller and speed PID controller in the feedforward control model are changed to non-smooth controller.

4.2 Simulation results

Fig. 9 shows the response curve with feedforward compensation. Fig. 10 shows the response curve with non-smooth controller. Simulation conditions are: step position command, amplitude 10 mm, simulation time 0.9 s. In the case of no load, the response curve is good because of no disturbance. In the experiment, about 50% of the middle load is setting, about 2000 N, and the direction of the load force is in phase with the moving direction of the actuator.

Although the feedforward compensation PID is used to improve the tracking performance of the system, the robust performance of PID control is poor and the accuracy tracking cannot be achieved.

Fig. 11 shows the response curve error of feedforward control, and Fig. 12 gives the error of the response curve of non-smooth

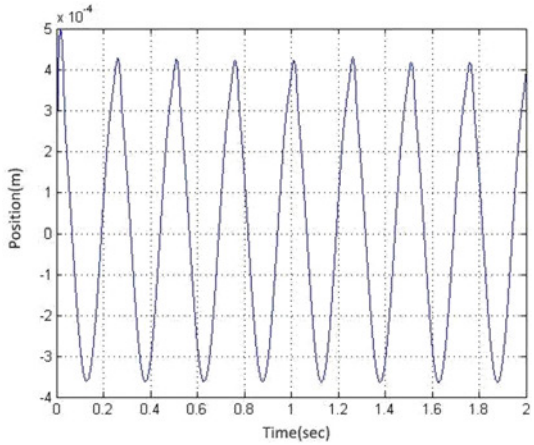


Fig. 9 *Response curve with feedforward compensation*

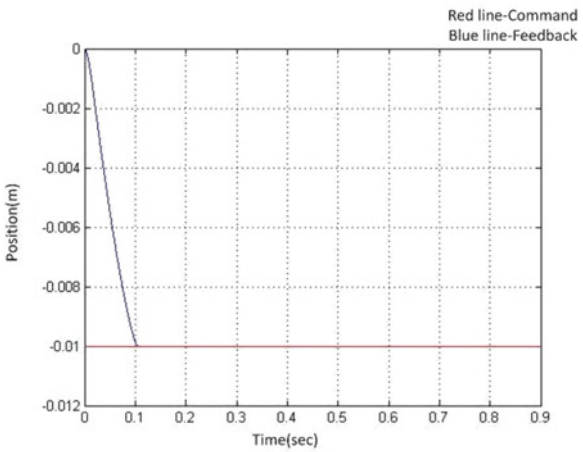


Fig. 10 *Response curve of non-smooth controller*

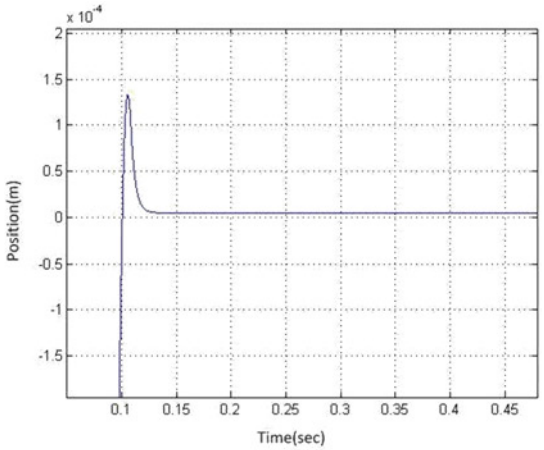


Fig. 11 *Response curve error of feedforward control*

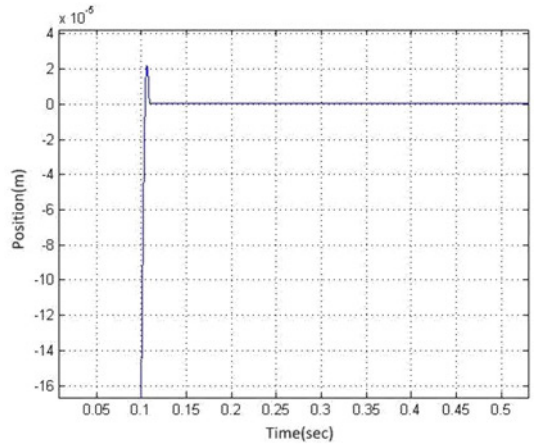


Fig. 12 *Error of the response curve of non-smooth control*

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control. Figs. 11 and 12 show that, under the same load, the static error of disturbance and tracking response with the non-smooth control is less than feedforward compensation, it is about 1/10 of the feedforward system, the convergence time is about 1/3 of feedforward compensation system. However, the arrival time lags behind. In the electromechanical servo system, the PID control of the position loop is replaced by non-smooth control, which has better disturbance resistance and fast convergence performance.

5 Conclusion

Based on the design method of electromechanical servo control system, the model in the loop is simulated with the mathematical model of the electromechanical actuator. The electromechanical servo system with PID control based on feedforward compensation is introduced. The following characteristics of EMA servo system have been improved obviously, but it cannot completely solve the problem of control in the control process. To solve this problem, the mechatronic servo system is presented based on non-smooth control. Through the analysis of simulation results, the non-smooth control of the servo system can ensure the system response, and can improve the tracking accuracy of the system at the same time.

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