Research on Electro-hydraulic Servo System of Air Rudder on Model Reference Adaptive Control

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Abstract. An adaptive control system with good following characteristics is designed for the electro-hydraulic servo system which are strongly coupled and seriously nonlinear. The model of position servo system on air rudder is discussed with the uncertain system equivalent to the one with parametric variable double input and single output to establish a Popov-MRAC (Model Reference Adaptive Control) system. The simulation results show that the Popov MRAC system has good following characteristics, precision and robustness.

1. Introduction
With the development of ballistic missile defense technology, the warhead's penetration and survivability have been greatly challenged. In recent years, major military powers in the world have intensified their research on missile penetration prevention technology and promoted the rapid development of warhead penetration technology [1]. The use of maneuvering warheads to avoid maneuverable warhead technology is a more effective breakthrough defense program. Compared with inertial aircraft, reentry maneuverable warheads are accompanied by large attack angles, large side slip angles, large rudder angles, and other flight attitudes, and flight altitude, Mach number, and other changes are dramatic. The dynamic performance of the air rudder position servo system of warheads Make higher demands.

The air rudder electrohydraulic servo system is a servo system with a valve-controlled hydraulic cylinder as the power element. It controls the rudder angle of the air rudder, changes the aerodynamic direction, generates the control torque, changes the attitude of the aircraft, and makes the maneuvering warhead press the command of the control system.

The electro-hydraulic servo system of the air rudder is a typical nonlinear time-varying system, which often has a large degree of parameter changes and large time-varying load interference. By using conventional PID control, the dynamic performance of the system is often difficult to meet the requirements.

Model Reference Adaptive Control (MRAC), as a relatively advanced control strategy, is used to solve the control problem of the performance specification defined by the reference model. It has been successfully applied to manipulator motion control, ship autopilot, aircraft control, etc. Field [2].
In this paper, taking the air rudder electro-hydraulic servo system as an example, the application of the model reference adaptive control strategy in the air rudder surface position servo system is studied, and its ability to ensure motion accuracy under external load disturbance is investigated.

2. Air Rudder Electro-hydraulic Servo System MODELING

Typical air rudder electro-hydraulic servo system is mainly composed of servo actuator, servo control actuator, electro-hydraulic energy source, servo battery and servo cable network. The essence of the system is "valve controlled cylinder" system. The control block diagram of the system is shown in Figure 1.

![Control structure diagram of servo system of air rudder](image)

**Figure 1.** Control structure diagram of servo system of air rudder

The key to mathematical modeling of electro-hydraulic servo system is to establish accurate servo valve model and control object load model. The valve-controlled cylinder hydraulic power element is a high-order, nonlinear, strongly coupled multi-variable system. Its actual dynamic mathematical model is a higher-order differential equation group.

2.1. Hydraulic servo valve modeling

Servo valves are devices with complex high-order nonlinear characteristics. In practice, the servo valve can be simplified to be equivalent to a first-order system or a second-order system. In an air-rudder electro-hydraulic servo system, the servo valve has a small time constant and a small damping coefficient, and the servo valve has a much wider bandwidth than the hydraulic pressure. The natural frequency, for simplicity, can ignore the dynamic characteristics of the servo valve and approximate the servo valve as a proportional link.

\[
G_{sv} = \frac{Q}{I} = K_{sv}
\]

Where \( G_{sv} \) is the transfer function of the servo valve; \( Q \) is the output flow of the servo valve; \( I \) is the current control signal; \( K_{sv} \) is the flow gain of the servo valve.

2.2. Hydraulic power mechanism modeling

Hydraulic power institutions model in the inertia load conditions, the air rudder surface of rotary movement equivalent to along the hydraulic cylinder the axis of the back and forth linear motion, air rudder electro-hydraulic position servo system can be equivalent to four-way valve control cylinder model, as shown in fig2.
According to reference 3, the transfer function model of the four-way valve control cylinder can be obtained as:

\[
X_p = \left[ \frac{K_x X_v - K_{cc} (1 + \frac{V_i}{4\beta_c K_{cc}}) s}{F_L} \right] \frac{s^2 + 2\xi_s s + 1}{s \left( \frac{4\beta_c A_p^2}{m V_i} \right)}
\]

\[
\omega_b = \sqrt{\frac{4\beta_c A_p^2}{m V_i}}
\]

\[
\xi_s = \frac{K_{cc} (\beta_c m V_i)}{A_p} + \frac{B_p}{4 A_p} \sqrt{\frac{V_i}{\beta_c m_i}}
\]

Where \(K_q\) is the servo flow gains; \(x_v\) is servo valve displacement; \(A_p\) is the hydraulic cylinder piston effective area; \(x_p\) is hydraulic cylinder piston displacement; \(V_i\) is the total compression volume; \(\beta_c\) is the effective bulk modulus; \(m_t\) is the piston equivalent mass; \(B_p\) is the viscous damping coefficient; \(F_L\) is the external load force.

In summary, The transfer function block diagram of the electro-hydraulic servo system of air rudder is shown in Figure 3.

![Figure 2. Four-way valve control cylinder dynamic mechanism](image)

![Figure 3. Block diagram of the electro-hydraulic servo system](image)
The main simulation parameters of the air rudder electro-hydraulic servo system are shown in Table 1.

**Table 1.** Styles Parameters Settings list of electro-hydraulic servo system of air rudder

| Symbol | Heading                  | Value | Units |
|--------|--------------------------|-------|-------|
| D      | Piston diameter          | 38    | mm    |
| d      | Piston rod diameter      | 24    | mm    |
| Ps     | Supply pressure          | 14    | MPa   |
| PL     | Load pressure            | 9.5   | MPa   |
| ρ      | Hydraulic oil density    | 870   | kg/m³ |
| β      | Bulk modulus             | 690   | MPa   |

3. Model Reference Adaptive Control System design

3.1. Model reference adaptive control principle

The main problem studied by the model reference adaptive control system is to design a stable, high-performance adaptive mechanism algorithm that not only ensures the stability of the system but also eliminates the generalized error. The essence of this kind of adaptive control system is to make the characteristics of the controlled closed-loop system consistent with the characteristics of the reference model. This often requires zero-pole cancellation in the closed-loop loop of the controlled system. Therefore, such systems are usually only applicable in the reverse stabilization system.

MRAC generally consists of a reference model, an object model, an adaptive law, and a control law. It corrects the control law parameters through an adaptive law, so that the output of the object model follows the reference model output.

3.2. MRAC-based air rudder electro-hydraulic servo system

Figure 4 shows the structure of the air rudder electro-hydraulic servo system using MRAC. For the air rudder electro-hydraulic servo system, the displacement can be directly measured by the line displacement sensor, and the speed can be measured indirectly through the rotary transformer. The acceleration can be obtained indirectly through mathematical calculation.

![Figure 4. Air rudder electro-hydraulic servo system block diagram using MRAC](image)

3.3. Electro-hydraulic servo system adaptive control law

3.3.1. Air rudder electro-hydraulic servo system model. The transfer function shown in Fig.3 represented by the state space equation as
Where $A_3, A_2, A_1, A_0$ and $B_0$ is the coefficients related to transfer function.

3.3.2. Reference Model and Equation of State. As an important part of the adaptive control system, the reference model needs careful selection according to the characteristics of the control object. Combined with the characteristics of the air rudder position servo control system, the system's requirements for the reference model are as follows:

a) The reference model order is the same as the object model, which is the third order;

b) The dynamic characteristics of the reference model meet the performance requirements of the air rudder position servo system;

c) In the servo system, position overshoot easily leads to damage to the servo mechanism. Therefore, the overshoot quantity indicator should be considered in the design.

Based on the above reasons, selecting the reference model that satisfies the dynamic performance requirements of the system is

$$y_m = \frac{A_1}{A_c(s)}u_m = \frac{M_0}{N_3s^3 + N_2s^2 + N_1s + N_0}u_m$$

The reference model's state equation is

$$\begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ -\frac{N_0}{N_3} & -\frac{N_1}{N_3} & -\frac{N_2}{N_3} & 0 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} u$$

Where $N_3, N_2, N_1, N_0$ and $M_0$ is the coefficients related to the reference model transfer function.

3.3.3. Determination of adaptive control law. In order to stabilize the designed adaptive control system in the sense of Popov, compensator $D(s)$ is introduced to make $D(s)/Am(s)$ strictly positive and true.

$$D(s) = d_2s^2 + d_1s + d_0$$

Then $D(s)$ should meet

$$\text{Re}\left[ \frac{D(j\omega)}{A_m(j\omega)} \right] > 0$$

Take the output signal of the state ,filter as $\zeta_1, \zeta_2, \zeta_3$,
ζ, the adaptive controller parameter adjustment rule is

\[ K_i = -\int_0^\infty \gamma_i \zeta_i e_i(t) dt \quad (i = 1, 2, 3, 4 \quad \gamma_i > 0) \]

The control input of the system is

\[ u(t) = \sum_{i=1}^4 K_i \zeta_i \]

Among them, take \( \zeta_1 = x_1 \), \( \zeta_2 = x_2 \), \( \zeta_3 = x_3 \), \( \zeta_4 = u_m \)

then constitute an adaptive control system as shown in Figure 5.

Figure 5. MRAC control diagram of air rudder electro-hydraulic servo system

4. Air Rudder Electro-hydraulic Servo System MODELING

Take the reference model as

\[ G_m(s) = \frac{384400}{s^3 + 240s^2 + 14400s + 384400} \]

Take the Compensator as

\[ D(s) = s^2 + 160s + 6000 \]

The model reference adaptive control system in Simulink is shown in Figure 6. Among them, the submodule "G(um)" represents the state space equation of the reference model, and the submodule "G(u)" represents the state space model of the controlled object. The submodule "G(F_L)" represents the state space equation of external load disturbance.
Figure 6. Simulink model diagram of model reference adaptive control system

During the working process of the actual air rudder electro-hydraulic servo system, the piston rod external load force $F_L$ is usually larger and varies. After calculation, the corresponding air rudder hinge moment of the system is about 500 Nm, and the thrust of the piston rod converted to hydraulic cylinder is 6400N.

A sinusoidal signal with an amplitude of 6400 and a frequency of 10 Hz was used in the simulation model to simulate the external load force $F_L$ acting on the piston rod of the hydraulic air by the rudder surface hinge moment. The step response curves of the PID controller and the MRAC controller under external load disturbance are shown in Fig. 7. It is not difficult to see that PID control is affected by the influence of external load disturbance force, and the system’s steady-state accuracy is poor: MRAC control system is not sensitive to external load disturbance force, transient response speed and steady-state accuracy are better, and it has better load disturbance Robustness.
5. Conclusion
In this paper, a model reference adaptive control method for electro-hydraulic servo system of air rudder based on Popov's super stability theory is proposed. By using this method, the accurate low order mathematical model of the air rudder rudder position servo system can be obtained. Through the comparative analysis of MRAC control and traditional PID control response curve, it verifies the good robustness of MRAC system, and lays a good foundation for improving the control performance of air rudder electro-hydraulic servo system and the further application of MRAC.

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