Research on model-free adaptive control of electro-hydraulic servo system of continuous rotary motor

XIAOJING WANG¹, YANG ZHANG² AND CHUNHUI LI²

¹ School of Mechanical-Electronic and Vehicle Engineering, Beijing University of Civil Engineering and Architecture, Beijing
² School of Mechanical and Power Engineering, Harbin University of Science and Technology, Heilongjiang

Corresponding author: Xiaojing Wang (e-mail: hitwangxiaojing@163.com)

This project was supported by National Natural Science Foundation of China (Grant No. 51975164)

ABSTRACT The model-free adaptive controller (MFAC) for continuous rotary electro-hydraulic servo motor was proposed to deal with uncertainties such as friction, leakage and noise. The model of electro-hydraulic servo motor system was replaced by universal model, and the structure adaptive control and parameter adaptive control were combined, and MFAC controller of the motor system was designed by using the input and output data of the system to realize the low speed and tracking control of the motor system. It is proved by simulation and experiment that MFAC controller effectively improves the low-speed stability and anti-interference ability of electro-hydraulic servo system compared with traditional PID control, and MFAC controller widens the frequency response of the system and realizes the precise control of continuous rotary motor servo system.

INDEX TERMS Continuous rotary motor, Electro-hydraulic servo system control, Model-free adaptive control, Universal model

I. INTRODUCTION

As the key equipment of simulation and test in aerospace field, simulation turntable can simulate all kinds of attitude of the aircraft in working state, which plays a very important role in the research of guidance system and has great strategic significance for national defense science and technology [1], [2]. As the core equipment of simulation turntable, continuous rotary electro-hydraulic servo motor is required to have good low-speed stability, high frequency response and position tracking accuracy [3]. But there are some uncertain factors such as friction, leakage, vibration, noise and other factors in continuous rotary motor electro-hydraulic servo system, which cannot achieve high-precision trajectory tracking [4], [5], [6]. Therefore, considering the uncertain factors of the motor system, it is necessary to design a reasonable controller to meet the accuracy and performance requirements of the aircraft when the system accuracy is the worst.

At present, electro-hydraulic servo system control was widely used in various fields, such as aerospace, vehicle engineering, robot and other fields [7], [8], [9]. In view of the uncertain factors in continuous rotary electro-hydraulic servo motor, quantitative feedback theory (QFT) was applied to the motor position control system in reference [10] to solve the uncertainty of the system and the interference caused by friction torque. In Ref [11], the nonlinear integral sliding mode robust control method based on RBF neural network was proposed to reduce the influence of system chattering. In Ref [12], LuGre dynamic friction model was used to improve the system and eliminate the influence of friction on the system performance. In Ref [13], PID-PFC controller was used to effectively suppress the interference of electro-hydraulic servo system. In Ref [14], a practical output feedback backstepping controller was proposed for the motion control of a hydraulic actuator with integration of a robust delay compensating feedback and an extended state observer. In Ref [15], a practical adaptive tracking controller without velocity measurement was proposed for electrohydraulic servomechanisms. The proposed ESO-based adaptive controller theoretically achieves an excellent asymptotic tracking performa. In Ref [16], the improved active disturbance rejection control was adopted to meet the accuracy requirements and tracking performance of the motor system under unknown strong nonlinear and uncertain strong disturbance factors, but the active disturbance rejection control was only applicable to low-order systems [17], [18]. Although the above method effectively improves the system performance, it still cannot avoid the influence of the mathematical model inaccuracy on the system.

Based on MFAC control idea, MFAC control strategy applied to continuous rotary electro-hydraulic servo motor is proposed. MFAC control theory refers to the use of dynamic
linear time-varying models instead of discrete-time nonlinear systems, and only the I/O data of the controlled system was used to realize MFAC of the nonlinear system [19], [20], [21]. In Ref [22], MFAC controller was designed for manipulators under different gravity, and its feasibility and effectiveness were verified by simulation. In Ref [23], MFAC controller was designed for the system with noise disturbance, and its real-time performance and anti-jamming were verified by simulation. The MFAC controller adds tracking differentiator in the feedback, and denoises the input signal to get the processed signal. Through this process, the influence of noise on the control law is reduced. In Ref [24], MFAC controller was designed to solve non-uniform distribution of air gap magnetic field of hybrid magnetic bearings. Simulation and experiments show that the controller has good stability and tracking accuracy.

Based on the problems existing in the above controllers and the idea of MFAC control, model-free adaptive control strategy is designed in this paper. The design of continuous rotary motor universal model, continuous rotary motor MFAC control law and pseudo partial derivative of continuous rotary motor system respectively ensures the control accuracy of continuous rotary electro-hydraulic servo motor system under unknown strong non-linearity and uncertain strong disturbance and meets the low speed performance of motor. Simulink simulation and experiments are used to verify the feasibility and effectiveness of the designed controller.

II. ESTABLISHMENT OF CONTINUOUS ROTARY MOTOR ELECTRO-HYDRAULIC SERVO SYSTEM MODEL

The principle block diagram of the single-channel electro-hydraulic position servo system of the continuous rotary electro-hydraulic servo motor is shown in Figure 1. Based on the linearization analysis of the various components of the system principle block diagram, the mathematical model of the electro-hydraulic position servo system of the motor is established.

![Block diagram of single channel electro hydraulic position servo system of continuous rotary electro hydraulic servo motor](image)

**A. ESTABLISHMENT OF MATHEMATICAL MODEL OF CONTINUOUS ROTARY MOTOR SYSTEM**

1. Mathematical model of electro-hydraulic servo valve

The electro-hydraulic servo valve is the key component of the motor system, which simplifies the servo valve, such as the following equation.

\[
G_{sv}(s) = \frac{Q_0(s)}{I(s)} = \frac{K_{sv}}{s^2 + 2\zeta_{sv}s + 1}
\]

Where, \(Q_0\) is the no-load flow, \(K_{sv}\) is the gain of the servo valve \(m^3/(s\cdot A)\), \(\omega_{sv}\) is the natural frequency of the servo valve \((rad/s)\), \(\zeta_{sv}\) is the damping coefficient of servo valve.

2. Valve port flow equation of servo valve

\[
Q_L(s) = K_{q}X_0(s) - K_{p}P_L(s)
\]

Where, \(Q_L\) is the load flow \(m^3/s\), \(K_q\) is the flow gain \(m^3/(s\cdot Pa)\), \(X_0\) is the spool displacement \(m\), \(K_p\) is the flow pressure coefficient \(m^3/(s\cdot Pa)\), and \(P_L\) is the external load pressure \((MPa)\).

3. Load flow continuity equation of motor

The load flow of the motor mainly consists of three parts, the flow \(Q_t\) generated when the motor is rotating, the leakage flow \(Q_L\) generated in the motor, and the flow \(Q_0\) generated by oil compression, so the following equation is given.

\[
Q_L(s) = D_m \theta(s) + C_m P_L(s) + \frac{T_f}{4\beta_L} P_L(s) s
\]

Where, \(D_m\) is radian displacement \(m^2/rad\), \(\beta\) is angular displacement \(rad\), \(C_m\) is the total leakage coefficient \(m^3/s\cdot Pa\), \(V_L\) is the volume of connecting pipe, motor and electro-hydraulic servo valve chamber \(m^3\), and \(\beta_L\) is the effective bulk modulus of elasticity \(Pa\).

4. Motor torque balance equation

Ignoring the friction and the quality of the oil, the following equation is obtained from Newton’s second law.

\[
D_m P_L(s) = J \frac{d\theta(s)}{dt} + B_m \theta(s) + G\theta(s) + T_L(s)
\]

Where, \(J\) is the total moment of inertia after the motor and external load are converted \((kg\cdot m^2)\), \(B_m\) is the viscous damping coefficient \((N\cdot m)/(rad/s))\), \(G\) is the spring stiffness of the load \((N/m/rad)\), and \(T_L\) is the external load torque acting on the motor \((N\cdot m)\).

5. Transfer function of power mechanism of valve-controlled motor

According to Equations (2), (3) and (4), the total output angular displacement \(\theta(s)\) of the motor under the action of spool displacement \(x_0(s)\) and interference \(T_L(s)\) can be obtained, as shown in the following Equation.

\[
\theta(s) = \frac{K_{e}}{4\beta_L} x_0(s) - \frac{K_{e}l}{\beta_L} \left(1 + \frac{V_f}{4\beta_L} \right) T_L(s)
\]

Where, \(K_{e}\) is the total flow-pressure coefficient \(m^3/(s\cdot Pa)\).

In the hydraulic system, no sliding friction occurs when the motor and the load are connected, so the load stiffness has no effect on the system, that is, consider \(G = 0\), under normal circumstances, \(B_m \cdot K_{e} \cdot \frac{D_m}{D_n} = 1\), and simplify Equation (5) to the following Equation.
natural frequency (rad/s), there is a time-varying parameter, there is the following equation.

\[ \omega_n = \sqrt{\frac{K_d}{D_m}} \theta(s) = \frac{K_d x_n(s) + K_{ce}(1 + \frac{V_i}{4\beta c}) T_L(s)}{s^2 + \frac{2\zeta \omega_n}{\omega_n} s + \omega_n^2} \]  

(6)

Where, \( \omega_n \) is the hydraulic natural frequency (rad/s), \( a_h = \sqrt{\frac{4\beta c D_m^2}{J Y_i}} \), and \( \bar{x}_h = \frac{K_{ce}}{D_m} \frac{J Y_i}{V_i} + \frac{B_m}{4D_m} \frac{V_i}{Y_i} \), \( \beta c \) is the hydraulic damping ratio (dimensionless).

The no-load flow of the motor \( Q_0 = K_d x_n \), it can be obtained from Equation (6) that the transfer function of the motor's output angular displacement in no-load is as follows.

\[ \frac{\theta(s)}{Q_0(s)} = \frac{\frac{1}{D_m}}{s^2 + \frac{2\zeta \omega_n}{\omega_n} s + \omega_n^2} \]  

(7)

6. Servo amplifier transfer function

In general, the servo amplifier is simplified as a proportional link.

\[ K_a = \frac{U(s)}{I(s)} \]  

(8)

Where, \( K_a \) is the servo amplifier gain (A/V).

The block diagram of the motor system is established by Equation (1), (6), (7) and (8). As shown in Figure 2, \( K_1 \) is the transfer function of the main controller.

FIGURE 2. Block diagram of system transfer function

According to Figure 1, the open-loop transfer function of the motor system can be obtained as follows.

\[ G_a(s) = \frac{K_a x_v}{s^2 + 21\zeta_0 \omega_0 s + \omega_0^2} \]  

(9)

Where, \( K \) is the open-loop gain of the system, \( K_a K_d K_{sv} D_m \).

The parameters of the motor system and other components are as follows, radial displacement \( D_m = 1.59 \times 10^4 \text{m}^2/\text{rad} \), load inertia \( J = 1.07 \times 10^4 \text{kg}\cdot\text{m}^2/\text{rad} \), hydraulic oil volume elastic modulus \( \beta_c = 7 \times 10^8 \text{N/m} \), effective volume \( V = 1.21 \times 10^8 \text{m}^3/\text{rad} \), natural frequency \( \omega_0 = 756.5 \text{rad/s} \), oil source pressure \( 10 \text{MPa} \), damping ratio \( \xi_v = 0.1 \), viscosity coefficient \( B_m = 5343 \text{N\cdotm/s} \), leakage coefficient \( \omega_0 = 7 \times 10^{-12} \text{m}^3/\text{s} \text{Pa} \), the model of electro-hydraulic servo valve is sfl-10, rated current of servo valve 8mA, rated oil hydraulic pressure 16MPa, rated flow 30L/min, servo valve flow gain \( K_{sv} = 0.04941 \text{m/s \cdot A} \), natural frequency \( \omega_0 = 276.5 \text{rad/s} \), damping ratio \( \xi_v = 0.6 \), output current of servo amplifier 8mA.

The servo valve is simplified as a proportional link, and the parameters are substituted into Equation (9) to obtain the transfer function of the system, which is the following equation.

\[ G(z) = \frac{0.1376z^2 + 0.2834 + 0.04599}{z^3 - 0.7901z^2 + 0.1143z - 0.129} \]  

(10)

The design process of the model-free adaptive controller is not based on the state of the motor, but a nominal model is required as the controlled object in the simulation. And the model-free adaptive controller uses the input and output of the system to establish a general model, so these parameters have no effect on the performance of the controller.

B. SYSTEM UNIVERSAL MODEL

The theoretical basis of MFAC control is universal model, which linearizes the non-linear system and controls the system.

The general SISO system is expressed as follows.

\[ y(k+1) = f(y(k), L, y(k-n), u(k), L, u(k-m)) \]  

(11)

Where, \( y(k) \) is the output of the system at k-time, \( k \) is the sampling period, \( u(k) \) is the input of the system at different times, \( m \) and \( n \) are the input and output orders of the system, and \( f(g) \) is the output function of the system.

The following assumptions are made by MFAC control theory.

Hypothesis 1: The partial derivatives of \( \phi \) with respect to exist and continue.

Hypothesis 2: System Equation (11) input and output must be observable and controllable.

Hypothesis 3: For any sampling period \( k \) and error rate \( \Delta u(k) \neq 0 \), there is the following equation.

\[ |\Delta y(k+1)| \leq b |\Delta u(k)| \]  

(12)

Where, \( \Delta y(k+1) = y(k+1) - y(k) \), \( \Delta u(k) = u(k) - u(k-1) \) and \( b \) is a constant.

Theorem 1: For a non-linear system equation (11), when \( \Delta u(k) \neq 0 \), there is a time-varying parameter \( \phi(k) \), and the following equation is obtained.

\[ \Delta y(k+1) = \phi(k) \Delta u(k) \]  

(13)

Where, \( |\phi(k)| \leq b \), \( b \) is a constant greater than zero.

Equation (13) is a universal model, and \( \phi(k) \) is the pseudo partial derivative (PPD). By Equation (13), Equation (11) is linearized and can be represented as follows.

\[ y(k+1) = y(k) + \phi(k) \Delta u(k) \]  

(14)

A MFAC controller can be theoretically designed by converting a complex motor system into a linear time-varying system with a single parameter through universal model transformation.

C. MFAC CONTROL LAW OF CONTINUOUS ROTARY MOTOR

In this study, the criteria function is selected as follows.

\[ J(u(k)) = \left[ y'(k+1) - y(k+1) \right] + \lambda \left[ u(k) - u(k-1) \right] \]  

(15)

Where, \( \lambda > 0 \) is the magnification factor of control output difference, which limits the input, \( y'(k+1) \) is the expected
output, which $y(k+1)$ is the actual output of the system, and $u(k)$ and $u(k-1)$ are the control variables at different times.

Substitute Equation (14) into Equation (15) and take the derivative of $u(k)$. When $\hat{J}(u(k)) / \hat{u}(u(k)) = 0$, we get the following Equation.

$$u(k) = u(k-1) + \frac{\rho \phi(k)}{\lambda + \phi(k)} \left\{ y'(k+1) - y(k) \right\}$$  \hspace{1cm} (16)

Where, $\rho \in (0,1)$ is the step factor and $\lambda$ is the control law parameter.

Equation (16) is the MFAC control law equation, and the pseudo-partial derivative $\phi(k)$ varies with input and output data. When the state of the system at different times is known, the desired output $y'(k+1)$ of the system can be obtained through the MFAC controller.

D. PSEUDO PARTIAL DERIVATIVE OF MOTOR SYSTEM

Because of the disturbance of linear uncertainty in the motor system, the requirement of criterion function is very high in the actual control process. From Ref [25], to ensure the rate of change of the pseudo partial derivative, the selection criterion function is as follows.

$$J(\phi(k)) = y'(k+1) - y(k) - \phi(k)\Delta u(k-1) + \mu \phi(k) \Delta \phi(k-1)^2$$  \hspace{1cm} (17)

When $\hat{J}(\phi(k)) / \hat{\phi}(\phi(k)) = 0$, the following equation can be obtained.

$$\phi(k) = \hat{\phi}(k-1) + \frac{2\rho \mu \Delta u(k-1)}{\mu + \phi(k-1)} \left[ \Delta y(k) - \hat{\phi}(k-1)\Delta u(k-1) \right]$$  \hspace{1cm} (18)

Where, $\eta$ is the step size of the control algorithm and $\mu$ is the weighting coefficient, usually $\mu \in (0,1)$. The pseudo partial derivative can change with the input and output, which ensures the accuracy of the controller.

III. DESIGN OF MFAC CONTROLLER FOR CONTINUOUS ROTARY MOTOR SYSTEM

A. SCHEME DESIGN OF MFAC CONTROLLER FOR CONTINUOUS ROTARY MOTOR SYSTEM

The universal model of the motor system instead of the mathematical model of the motor system is as follows.

$$\theta(k+1) = f \left( \theta(k), L, \theta(k-n), u(k), L, u(k-m) \right)$$  \hspace{1cm} (19)

Where, $\theta(k)$ is the output of the system, $u(k)$ is the input of the system, $m$ and $n$ is the order of input and output respectively.

When the motor system meets Hypothesis 1~3, according to Equations (16) and (18), the control function of MFAC to the motor system can be obtained as follows.

$$\phi(k) = \hat{\phi}(k-1) + \frac{2\rho \mu \Delta u(k-1)}{\mu + \phi(k-1)} \left[ \Delta y(k) - \hat{\phi}(k-1)\Delta u(k-1) \right]$$  \hspace{1cm} (20)

Make $\epsilon$ a very small number, then $\hat{\phi}(k) = \phi(1)$ when $\phi(k) \leq \epsilon$ or $| \Delta u(k) | \leq \epsilon$.

$$u(k) = u(k-1) + \frac{\rho \phi(k)}{\lambda + \phi(k)} \left\{ \theta'(k+1) - \theta(k) \right\}$$  \hspace{1cm} (21)

Where, $\phi(k)$ is the real-time change value of pseudo-partial derivative, $\phi(1)$ is the starting point of estimation, $\eta$ and $\rho$ are control factors which are all positive numbers less than 1, $\mu$ and $\lambda$ are the weights of the controller. $\theta'(k+1)$ is the expected output of electro-hydraulic servo system at all times, $\Delta \theta(k) = \theta(k) - \theta(k-1)$, $\Delta u(k-1) = u(k-1) - u(k-2)$.

The schematic diagram of MFAC controller of motor system is shown in Figure 1. By processing the expected input signal, expected output signal and control quantity at the previous moment, the control output quantity at the next moment is obtained.

In Figure 3, the structure of the MFAC controller is designed by Equation (20) and (21). Figure 4 is internal structure of controller. In Figure 4, the input, output and control quantity of the time are taken as inputs to be the output control quantity of the time.

B. CONVERGENCE AND STABILITY OF MFAC CONTROLLER FOR CONTINUOUS ROTARY MOTOR SYSTEM

The stability of control algorithm is very important to the control performance of motor system. It is necessary to study the astringency and stability of MFAC control system. The convergence of MFAC algorithm can be expressed by Theorem 2.

Theorem 2: the stability conditions of MFAC algorithm composed of Equation (20) and Equation (21) are as follows.

$$(1) \quad \theta(k+1) - \hat{\theta}(k+1) \leq M | \Delta u(k) |$$  \hspace{1cm} where $M$ is a constant.

(2) When $\theta^* (k+1)$ is a constant, $\eta$, $\mu$, and $\rho$ take appropriate values, there is a number $\lambda_{\text{min}}$ larger than zero. When $\lambda > \lambda_{\text{min}}$, the system is stable within certain boundaries.

Proof: First, prove that $\phi(k)$ is bounded.

When $| \Delta u(k) | \leq \epsilon$, it can be known from $\phi(k) = \phi(1)$ that $\phi(k)$ must be bounded.

When $| \Delta u(k) |> \epsilon$, the estimated value $\phi(k)$ is subtracted from both sides of Equation (20), making $\bar{\phi}(k) = \phi(k) - \phi(k)$, Equation (20) can be rewritten into the following equation.

$$\bar{\phi}(k) = \phi(k-1) - \phi(k) + \frac{2\rho \mu \Delta u(k-1)}{\mu + \phi(k-1)} \left[ \Delta y(k) - \hat{\phi}(k-1)\Delta u(k-1) \right]$$  \hspace{1cm} (22)

The Equation (13) is substituted into Equation (22), and the following equation is obtained by Theorem 2.
Where, \( b \) is an appropriate number, when \( \mu > 0 \), \( \eta \equiv (0,1] \), the following equation can be established.

\[
0 < 1 - \frac{\eta \Delta u(k-1)}{\mu + |\Delta u(k-1)|^2} \leq d < 1
\]

(24)

Where, \( d \) is a constant greater than zero.

From Equation (23) and (24), the following equation can be obtained.

\[
\overline{\phi}(k) \leq d \overline{\phi}(k-1) + 2b \leq 2d^2 \overline{\phi}(k-2) + 2db + 2bd \leq d^k(1) + \frac{2b}{1-d}
\]

(25)

From Equation (25), it can be obtained that when \( d < 1 \), \( |\overline{\phi}(k)| \) must be bounded, and \( \phi(k) \) must be bounded, so \( \overline{\phi}(k) \) is bounded. Since \( \phi(k) \) and \( \dot{\phi}(k) \) are bounded and \( \phi(k) \leq \varepsilon \) combined Equations (14) and (21), the following equation can be obtained.

\[
\theta(k+1) - \dot{\theta}(k+1) \leq M|\Delta u(k)|
\]

(26)

Where, \( M \) is constant and upper limit of \( \left| \dot{\phi}(k) \right| \), the stability condition (1) is proved.

It can be known from Equation (21) that:

\[
\Delta u(k) = \frac{\rho + \phi(k)}{\lambda + \phi^2(k)} \left( \theta^* - \dot{\theta}(k) \right)
\]

(27)

Make the difference between the two sides of Equation (14) and the expected output signal \( y^* \), and put into Equation (27), and make \( \varepsilon(k) = \left| \dot{\theta}(k) - \dot{\theta}(k) \right| \), then the equation can be expressed as the following equation.

\[
\varepsilon(k+1) \leq \frac{\rho + \phi(k)}{\lambda + \phi^2(k)} \varepsilon(k)
\]

(28)

From the MFAC algorithm, \( \phi(k) \dot{\phi}(k) \geq 0 \), then there are appropriate \( \rho \) and \( \lambda \), which makes the following equation true.

\[
0 < 1 - \frac{\rho + \phi(k)}{\lambda + \phi^2(k)} \leq f < 1
\]

(29)

The following equation can be derived from Equation (20) and (21).

\[
\varepsilon(k+1) \leq f \varepsilon(k) \leq f^2 \varepsilon(k-1) \leq f^k \varepsilon(1)
\]

(30)

It can be concluded that the algorithm is convergent when \( \lim_{k \to \infty} \varepsilon(k+1) = 0 \).

From Equation (21) and (30), it can be known that there must be \( N \) sufficiently large constant \( N = \frac{\rho + \phi(k)}{\lambda + \phi^2(k)} \), and the following equation can be obtained.

\[
| \Delta u(k) | \leq N \varepsilon(k) + N \varepsilon(k-1) + L + N \varepsilon(2) + | u(1) | + N \varepsilon(1) - \frac{f \varepsilon(1)}{1-d^2} + | u(1) |
\]

(31)

It can be seen from Equation (31) that the control input \( u(k) \) is bounded, so the performance of the MFAC controller is convergent and stable.

C. PARAMETER SETTING OF MFAC CONTROLLER FOR CONTINUOUS ROTARY MOTOR SYSTEM

The MFAC controller simulation block diagram of the continuous rotary motor is built in Simulink. The motor system MFAC controller structure diagram is shown in Figure 5. (a) is the MFAC general control diagram of the continuous rotary motor system, and Figure 4 (b) is the MFAC internal structure diagram of continuous rotary motor system. The slope signal and sine signal of different frequencies are used as input signals to study the performance of the controller. In this study, initial condition \( e \) is set to \( e = 10^{-5} \), and the parameters to be determined are \( \phi(1) \), \( \eta \), \( \mu \), \( \rho \) and \( \lambda \). \( \phi(1) \) is the initial iteration value of pseudo-partial derivative \( \dot{\phi} . \eta \) is the step factor, which makes the algorithm more flexible and easier to fit each system. Constant \( \mu \) avoids zero denominator and also adjusts the estimated value of pseudo-partial derivative. \( \rho \) and \( \eta \) work the same way. \( \lambda \) can be used to limit the control input \( \Delta u(k) \) and ensure the input of motor system certain smooth. Proper selection of \( \lambda \) can make the system more stable and have good output performance.

IV. SIMULATION STUDY OF MFAC CONTROLLER FOR CONTINUOUS ROTARY MOTOR SYSTEM

A. RAMP SIGNAL SIMULATION RESEARCH

In order to study the low-speed performance of the MFAC controller, a ramp signal of 0.001°/s was used as the input signal in Simulink to obtain the output characteristic comparison curve of the MFAC controller and the PID controller, as shown in Figure 6.
From Figure 6, it can be seen that under the action of PID controller, the tracking speed of motor system is slower and the static error after stabilization is larger than that of MFAC controller. Under the function of MFAC, the tracking speed of the system is fast and the static error of the system meets the requirements of low-speed performance, which proves that MFAC controller can effectively control the motor system. Through the simulation of ramp signal, it is proved that the low-speed performance of MFAC controller is better than PID controller.

**B. SINUSOIDAL SIGNAL SIMULATION RESEARCH**

The sinusoidal signal with amplitude of 1° and frequency gradually increasing is used as the input signal to simulate the MFAC controller of continuous rotary motor system, and the output comparison curves of PID control and MFAC are obtained as shown in Figures 7 to 13. Where figure (a) is the sinusoidal response curves of the motor system, and figure (b) is the sinusoidal response curves of the motor system with a single period.

**FIGURE 6. Simulation comparison chart of ramp signal under MFAC control**

**FIGURE 7. MFAC control response curves of sinusoidal signal of motor system at 8Hz and 1°**

**FIGURE 8. MFAC control response curves of a single cycle motor system at 8Hz and 1°**

**FIGURE 9. MFAC control response curve of sinusoidal signal of motor system at 10Hz and 1°**

**FIGURE 10. MFAC control response curves of a single cycle motor system at 10Hz and 1°**

**FIGURE 11. MFAC control response curves of sinusoidal signal of motor system at 12Hz and 1°**

**FIGURE 12. MFAC control response curves of a single cycle motor system at 12Hz and 1°**

**FIGURE 13. MFAC control response curves of sinusoidal signal of motor system at 14Hz and 1°**

**FIGURE 14. MFAC control response curves of a single cycle motor system at 14Hz and 1°**
This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3160830, IEEE Access

This work is licensed under a Creative Commons Attribution 4.0 License. For more information, see https://creativecommons.org/licenses/by/4.0/

FIGURE 10. MFAC control response curves of sinusoidal signal of motor system at 11Hz and 1°

FIGURE 11. MFAC control response curves of sinusoidal signal of motor system at 12Hz and 1°

FIGURE 12. MFAC control response curves of sinusoidal signal of motor system at 13Hz and 1°

FIGURE 13. MFAC control response curves of sinusoidal signal of motor system at 14Hz and 1°

The simulation results show that both PID control and MFAC controller can satisfy the control performance of the system. When the frequency of input signal is the same, the amplitude error under MFAC control is smaller than that under PID control and the phase lag is larger than that under PID control. As the frequency of input signal increases, the control effect of both controllers becomes worse. Data analysis of the output signal is shown in Table 1.

TABLE 1 Comparison of system performance with amplitude of 1°

| Frequency (Hz) | Amplitude error (%) | Phase error (°) |
|---------------|---------------------|----------------|
| 8             | 5.11                | 1.455          |
| 9             | 6.19                | 2.091          |
| 10            | 7.11                | 3.113          |
| 11            | 7.92                | 4.431          |
| 12            | 8.59                | 6.158          |
| 13            | 9.13                | 6.719          |
| 14            | 9.92                | 7.202          |

From Table 1, it can be seen that the response frequency of MFAC can reach 14Hz under the condition of satisfying the double ten indexes, and the comprehensive performance is better than that of PID controller. The simulation results show that MFAC controller can effectively improve the low speed performance and tracking performance of the motor system, and can achieve accurate control.

V. EXPERIMENTAL VERIFICATION OF MFAC CONTROLLER FOR CONTINUOUS ROTARY MOTOR SYSTEM

Through the simulation of slope signal and sinusoidal signal, compared with PID, PID control and MFAC controller can meet the control performance of the system, but MFAC control performance is better than PID control, with better low-speed performance and tracking performance. Therefore, the main purpose of motor experiment is to verify whether MFAC controller can effectively track the system and improve motor performance without any compound controller.

VOLUME XX, 2017
A. INTRODUCTION TO EXPERIMENTAL SYSTEM

The motor experiment platform is mainly composed of hydraulic components, electronic components, and motor systems. Hydraulic components include axial piston pump, continuous rotary motor, electro-hydraulic servo valve and hydraulic auxiliary devices, such as accumulator, safety element, oil filter, hydraulic pressure gauge and other components. Electronic components mainly include photoelectric code plate, signal generator, data acquisition card and data conversion card. The continuous rotary motor test bench is shown in Figure 14.

![Figure 14. Continuous rotary motor test bench](image)

B. RAMP SIGNAL EXPERIMENT

The low speed tracking performance of MFAC controller is verified by ramp input signal. The motor is studied with the slope signals of 0.05°/s, 0.01°/s, 0.005°/s and 0.001°/s, respectively. After collecting the experimental data, the experimental diagram is shown in Figure 15, where straight lines 1 and 2 are the allowable error bands during the experiment.

![Figure 15. Experimental results of MFAC controller with ramp signal](image)

C. SINUSOIDAL SIGNAL EXPERIMENT

In order to verify the frequency response characteristics of MFAC controller, the sinusoidal signal with frequency of 8 to 12Hz and amplitude of 0.2 ° is selected as the input signal to carry out MFAC controller experiment on continuous rotary motor. When the system runs stably, the input and output data of continuous rotary motor are collected. After collecting the experimental data, the MFAC experimental diagram of continuous rotary motor is obtained, as shown in Figure 16 to 20. The solid line is experimental input signal, and the dot line is MFAC controller experimental output signal.

![Figure 16. Experiment results of 8Hz and 0.2 °](image)
The article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/ACCESS.2022.3160830, IEEE Access

Author Name: Preparation of Papers for IEEE Access (February 2017)

This page contains text about simulation errors and experimental results of MFAC controller. The table compares simulation and experimental results of MFAC controller for different input signal frequencies. The figures show experimental results of various frequencies and phase errors. The conclusion discusses the effectiveness of MFAC controller in controlling continuous rotary motor systems. The references include several papers on control systems and simulation methodologies.

VI. CONCLUSIONS

According to the idea of model free adaptive control, MFAC controller for continuous rotary electro-hydraulic servo motor is designed. The universal model is used to replace the mathematical model of the motor system, and the structure and parameter adaptive control ideas were combined to achieve precise control. It is proved through the simulation that MFAC controller can effectively improve the low-speed performance and tracking performance of the motor system. Under the condition of meeting the double ten index, the response frequency of MFAC can reach 14 Hz, which can meet the performance requirements of the motor system. Finally, the experimental verification is carried out by MFAC controller. The experimental results show that the designed continuous rotary motor MFAC controller can effectively control the motor in the presence of external interference such as friction and leakage, which can improve the performance of the motor.

REFERENCES

[1] Y. Wang, X. Zhang, G. Zhang, and Y. Gao. “Design of Software Control System of Flight Simulation Turntable,” Computer Measurement & Control, vol. 25, no. 6, pp. 104-106+123, 2017.

[2] S. Han, Z. Jiao, C. Wang, and Y. Shi. “Integral sliding mode nonlinear controller of electrical-hydraulic flight simulator based on neural network,” Journal of Beijing University of Aeronautics and Astronautics, vol. 40, no. 3, pp. 321-326, 2014.

[3] J. Cao, S. Li, and K. Zhao. “Study on a new type of continuous rotary electro-hydraulic servo motor applied to simulator,” Journal of Astronautics, vol. 4, pp. 374-377+403, 2003.

[4] J. Ma, S. Li, J. Kai, and K. Zhao. “Research on low-speed frictional property of continuous rotary electro-hydraulic servomotor applied to simulator,” Acta Aeronautica et Astronautica Sinica, vol. 4, pp. 361-363, 2000.

[5] X. Liu, Y. Wu, D. Tian, and J. Wang. “Research of Sliding Mode Controller for Flight Simulator Based on Disturbance Observer,” Journal of Shanghai Jiaotong University, vol. 45, no. 3, pp. 393-397+402, 2011.

[6] B. Wang, K. Zhao, and J. Cao. “Robust control of hydraulic simulators using a μ-synthesis approach,” Journal of Harbin Engineering University, vol. 29, no. 2, pp. 158-161+166, 2008.

[7] J. Hu, F. Li, G. Wei, P. Gao, and Q. Cao. “Theory and applications of backstepping sliding mode variable structure control for uncertain systems,” Systems Engineering and Electronics, vol. 36, no. 3, pp. 519-526, 2014.

[8] D. Heng, Y. Cheng, S. Huang, M. Wu, H. Huang, and Y. Li. “Pressure control of electro-hydraulic servo loading system in heavy vehicle steering test board based on integral sliding mode control,” Proceedings of the Institution of Mechanical Engineers, vol. 234, no. 2-3, pp. 458-468, 2019. doi: 10.1177/0954407019859960.

[9] X. OuYang, B. Fan, H. Yang, and S. Ding. “A novel multi-objective optimization method for the pressurized reservoir in hydraulic robotics,” Journal of Zhejiang University-Science A (Applied Physics & Engineering), vol. 17, no. 6, pp. 454-467, 2016. doi: 10.1631/jzus.A1600034.
[10] Z. Wang, “Application of QFT Controller in Continuous Rotary Motor Position Servo,” Ship Electronic Engineering, vol. 32, no. 3, pp. 123-125, 2012.

[11] S. Han, Z. Jiao, C. Wang, and Y. Shi. “Integral sliding mode nonlinear controller of electrical-hydraulic flight simulator based on neural network,” Journal of Beijing University of Aeronautics and Astronautics, vol. 40, no. 3, pp. 321-326, 2014.

[12] L. Yuan, J. Guan, and L. Yuan. “Study on Random Vibration Control fora Hydraulic Angular Vibration Table Driven by a Continuous Rotary Electro-hydraulic Servomotor,” Molecular Systems Biology, vol. 5, no. 1, pp. 305, 2012.

[13] X. Wang, M. Liu, S. Chen, H. Liu, and W. Xin. “PID-PFC control of continuous rotary electro-hydraulic servo motor applied to flight simulator,” The Journal of Engineering, vol. 13, 2019. doi: 10.1049/joe.2018.8984.

[14] Deng W, Yao J, Wang Y, Yang X, Chen J. Output feedback backstepping control of hydraulic actuators with valve dynamics compensation[J]. Mechanical Systems and Signal Processing, 2021, 158.

[15] Deng W, Yao J. Extended-State-Observer-Based Adaptive Control of Electro-Hydraulic Servomechanisms without Velocity Measurement[J]. IEEE/ASME Transactions on Mechatronics, 2019, PP(99).

[16] Y. Sun. “Research on Identification and Active Disturbance Rejection Control of Continuous Rotary Electro-Hydraulic Servo Motor,” M.S. thesis, Dept. Mech. Eng. Harbin University of Science and Technology, Harbin, China, 2020.

[17] J. Liu, Z. Yang, and D. Li. “A multiple search strategies based grey wolf optimizer for solving multi-objective optimization problems,” Expert Systems With Applications, vol. 145, 2020. doi: 10.1016/j.eswa.2019.113134

[18] T. A. Rashid, D. K. Abbas, and Y. K. Turel. “A multi hidden recurrent neural network with a modified grey wolf optimizer,” plos one, vol. 14, no. 3, 2019. doi: 10.1371/journal.pone.0213237.

[19] H. Wang, J. Lian, and H. Xia. “A Model-Free Adaptive Control Approach of a Class of Non-Uniformly Sampled Nonlinear Systems,” Acta Electronica Sinica, vol. 46, no. 4, pp. 814-818, 2018.

[20] X. Wei, N. Li, and W. Ding. “Chaos control of a non-smooth system based on model-free adaptive control method,” Journal of Vibration Engineering, vol. 31, no. 06, pp. 996-1005, 2018.

[21] H. Gao, G. Ma, Y. Lyu, and Y. Guo. “Data-driven model-free adaptive attitude control of partially constrained combined spacecraft with external disturbances and input saturation,” Chinese Journal of Aeronautics, vol. 32, no. 5, pp. 1281-1293, 2019. doi: 10.1016/j.cja.2019.01.018.

[22] Y. Wen, L. Gao, F. Liu, and L. Qin. “Model-free adaptive control of space manipulator under different gravity environment,” High Technology Letters, vol. 26, no. 1, pp. 53-60, 2020. doi:10.3772/j.issn.1006-6748.2020.01.007.

[23] N. Dong, and S. Zhu. “Model-free Adaptive De-noising Control and Its Application,” Journal of Human University(Natural Sciences), vol. 47, no. 8, pp. 74-81, 2020.

[24] Y. Yuan, Y. Sun, Q. Xiang, Y. Huang, Z. Zhu. “Model-free adaptive control for three-degree-of-freedom hybrid magnetic bearings,” Frontiers of Information Technology & Electronic Engineering, vol. 18, no. 12, 2017. doi: 10.1631/FITEE.1700324.

[25] Z. Hou, S. Jin. “Model-free adaptive control based on dynamic linearization of compact scheme,” in Model-free adaptive control theory and application, 1st ed. Beijing, China: Science Press, Jun, 2013, ch. 4, sec. 2, pp. 54-55.

XiaoJing Wang
Professor
School of Mechanical and Power Engineering of Harbin University of Science and Technology, Harbin, China
Xiaojing Wang received the Doctor degree from Harbin Institute of Technology in 2009

Her research interests include Fluid Power Transmission and Control, New Type Hydraulic Component, Continuous Rotary Electro hydraulic Servo Motor and Electro hydraulic Servo System Control.

Yang Zhang
School of Mechanical and Power Engineering, Harbin University of Science and Technology, Harbin, China
Yang Zhang received the B.Sc. degree from Harbin University of Science and Technology in 2020. Respectively, where he is currently pursuing the M.Sc. degree under the supervision of Prof. Xiaoqing Wang.

His research interests include electro-hydraulic servo system control and fluid simulation.

ChunHui Li
School of Mechanical and Power Engineering, Harbin University of Science and Technology, Harbin, China
He received the B.Sc. degree from Harbin University of Science and Technology in 2021, respectively, where he is currently pursuing the M.Sc. degree under the supervision of Prof. Xiaoqing Wang.

His research interests include electro-hydraulic servo system control and continuous rotary hydraulic motor.