Research on Sliding Mode-PID Composite Control Optimization of Electro-Hydrostatic Actuator

Li Jing[1, a], Hong Hui[2,b], Xin Donghua[3,c]
[1,2,3]Tongji University, No. 4800 Caoan Road, Jiading District, Shanghai, China
[a]cynthia_li@tongji.edu.cn, [b]1365157825@qq.com, [c]506170961@qq.com

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Abstract. Electro-Hydrostatic Actuator (EHA) has developed rapidly in airborne flight control systems due to its compact structure, high energy efficiency and easy control. However, because of the strong nonlinearity of EHA system and external uncertainties, simple PID control cannot achieve the ideal control requirements. This paper proposes a composite control system that controls the actuator cylinder position with sliding mode and motor speed with PID. Sliding-mode position controller structure is designed, and an adaptive genetic algorithm is used to optimize the composite control parameters. The simulation results show that the optimized sliding mode-PID composite control can eliminate the overshoot, suppress the external interference and achieve the precise control of EHA position.

1. Introduction

Electro-Hydrostatic Actuator (EHA) is a kind of integrated power-by-wire (PBW) actuator which reduces pipelines, increases energy efficiency and aircraft survivability[1]. It will play an important role in the airborne system of more electric aircraft [2]. The variable motor fixed pump (VMFP)-EHA is widely used due to its simple structure and high-efficiency.

EHA controlling is difficult since its complex nonlinearity and uncertain alternating load in the flight control system[3]. To improve the dynamic performance of EHA, scholars designed a lot of nonlinear controllers beyond PID controlling, such as adaptive control[4] and fuzzy control[5].

This paper designs a sliding mode-PID composite controller for VMFP-EHA system. A sliding mode position controller is designed, and the adaptive genetic algorithm is applied to optimize the controlling parameters. And the effectiveness of this method is verified by the simulating.

2. Sliding Mode-PID Composite Control

Fig. 1 is the schematic diagram of a VMFP-EHA system. The controller generates commands according to the feedback of pressure, current, speed and actuator position. The power driving circuit controls the motor speed, then it drives the pump to transfer the oil to actuator to control its position.

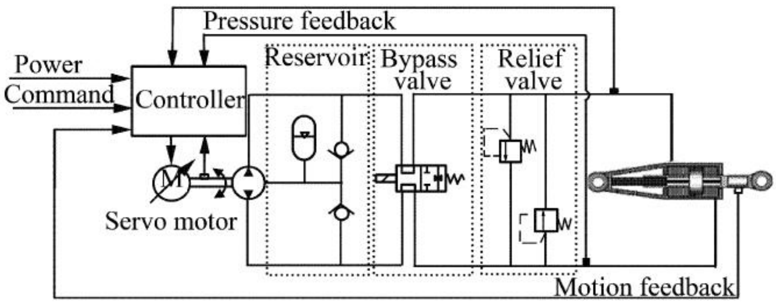


Fig. 1 Schematic diagram of FPVM-EHA

2.1 Composite Control System Design. The ultimate control target of EHA system is to make the actuator position meet the requirements of accuracy, quickness and stability. Due to the strong non-linearity of EHA system and the uncertainty of external load, traditional PID position control can not reach a satisfied achievement.

This paper proposes a sliding mode-PID composite control system, as shown in Fig. 2. The inner loop of the control system is composed of a current loop and a speed loop. The PI controller is used to realize motor speed control; the outer loop is a position feedback loop, in which the sliding mode controller substitutes the PID controller to improve the system's rapidity and robustness.

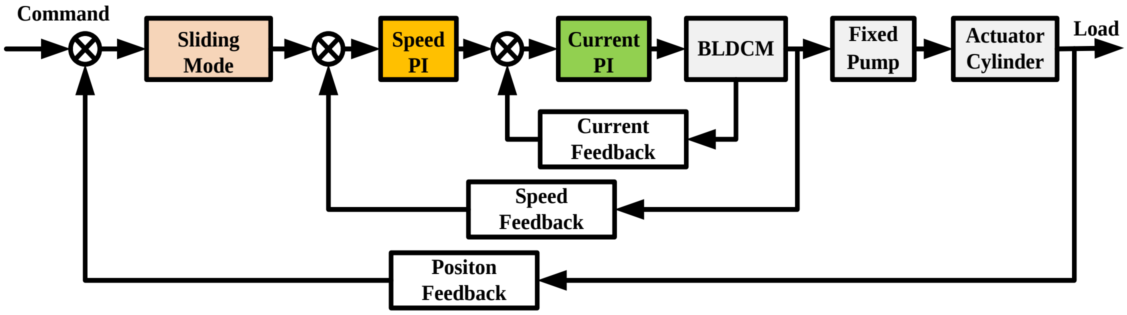


Fig. 2 Block diagram of sliding mode-PID composite control system

2.2 Sliding Mode Controller Structure Design. The controller structure design can be divided into two processes: a. design the switching function $s(x)$; b. design the control law $u(x)$.

a. Switching function design.

Taking the actuator position, velocity, and acceleration as the state vectors, it turns into a third-order system.

$$x_1 = x_t, x_2 = \dot{x}_t, x_3 = \ddot{x}_t \,. \tag{1}$$

The state equation can be obtained from EHA model:

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 \\ \dot{x}_3 &= -\frac{B_t}{M}x_3 - \frac{2A_t^2E_y}{MV_t}x_2 - \frac{\dot{F}_L}{M} - \frac{2A_tE_y(\xi + 1/2L_e)}{MV_t}(p_1 - p_2) + \frac{2A_tE_yD_p}{MV_t}\omega \end{aligned} \,. \tag{2}$$

Where ξ is pump internal leakage coefficient, L_e the pump and hydraulic cylinder external leakage coefficient, A_t the piston force area, P_1, P_2 the cavity pressure, V_t the mean volume of cylinder and oil pipeline, E_y the equivalent elastic modulus, B_t the viscous damping coefficient, F_L the load force.

Assuming the given input signal is x_d , the error and its derivatives are

$$e = x_d - x_t = x_d - x_1 \,,\ \dot{e} = \dot{x}_d - \dot{x}_t = \dot{x}_d - x_2 \,,\ \ddot{e} = \ddot{x}_d - \ddot{x}_t = \ddot{x}_d - x_3 \,. \tag{3}$$

This paper designs switching function s as a linear combination of the error variables

$$s = CE \,. \tag{4}$$

Where $C = [c_1 \ \ c_2 \ \ 1]$, error vector $E = [e \ \ \dot{e} \ \ \ddot{e}]$, the following equations can be drawn:

$$s = c_1e + c_2\dot{e} + \ddot{e} = c_1(x_d - x_1) + c_2(\dot{x}_d - x_2) + \ddot{x}_d - x_3 \,. \tag{5}$$

The reasonable value of matrix C has a great influence on the dynamic quality of the sliding mode. This paper uses the pole configuration method to determine the value, set the predetermined pole as $\Lambda = \{\lambda_1, \lambda_2\}$, the following equations can be drawn:

$$\lambda_1\lambda_2 + c_1 + c_2\lambda_2 = 0\,. \tag{6}$$

As can be seen from the above equation, the values of c_1 and c_2 are not unique.

b. Control law design.

This paper adopts exponential reaching law to design control law *u*.

$$\dot{s} = c_1(\dot{x}_d - x_2) + c_2(\ddot{x}_d - x_3) + \dddot{x}_d - \dot{x}_3 = -\varepsilon\,\mathrm{sgn}(s) - ks,\quad \varepsilon > 0\ \ k > 0\,. \tag{7}$$

Where ε is the speed parameter, *k* the arrival parameter.

Substituting Eq. (7) into Eq. (1) and (2) yields a control law expression

$$u = \frac{MV_t}{2A_tE_yD_p}\begin{bmatrix} c_1e + c_2\dot{e} + \ddot{x}_d + \dfrac{B_t}{M}\ddot{x}_t + \dfrac{2A_t^2E_y}{MV_t}\dot{x}_t + \dfrac{\dot{F}_L}{M} \\ +\dfrac{2A_tE_y(\xi + 1/2L_e)}{MV_t}(p_1 - p_2) + \varepsilon\,\mathrm{sgn}(s) + ks \end{bmatrix}. \tag{8}$$

From Eq. (8), it can be seen that the values of *k*, ε, c_1 and c_2 are not unique, and directly affect the system control performance. Therefore, this paper uses adaptive genetic algorithm (AGA) to optimize tuning of these four parameters and the PID control parameters of inner loop.

3. Optimization of Control Parameters Tuning

The optimized parameters in current PI, speed PI and position sliding mode are as follows: speed loop: K_{np}, K_{ni}; current loop: K_{ip}, K_{ii}; position loop: c_1, c_2, k, ε.

Here the objective function is based on the ITAE index, which is the integral form of the product of error function $e(t)$ and time. The rise time t_u ensures rapid response of the system; the control output $u(t)$ prevents the output from too large and destabilize; the overshoot amount $|e(t)|$ is the penalty term of the objective function to suppress overshoot. The final objective function is

$$J = \begin{cases} \int_0^\infty (\omega_1 t|e(t)| + \omega_2 u^2(t))dt + \omega_3 t_u & e(t)>0 \\ \int_0^\infty (\omega_1 t|e(t)| + \omega_2 u^2(t) + \omega_4|e(t)|)dt + \omega_3 t_u & e(t)<0 \end{cases}. \tag{9}$$

Where ω_1, ω_2, ω_3, ω_4 are the weight values, which adjust the influence degree of different performance indicators on the objective function. This paper takes ω_1=0.9, ω_2=0.02, ω_3=0.001, ω_4=100.

Since the objective function is supposed to be as small as possible, the fitness function defines as:

$$F(x) = \frac{1}{1+J}\,. \tag{10}$$

4. Simulation and Analysis

The EHA system simulation parameters are shown in Table 1.

The maximum fitness value in the optimization process is shown in Fig. 3.The step signal and sinusoidal signal are given respectively to analyze the response characteristics of the control system.

a. Step response analysis.

The position command is a 10mm step signal, the AGA optimized three-loop PID control (PI controller for the current loop and speed loop, PID controller for the position loop) and the un-optimized composite control are compared. The simulation results are shown in Fig. 4. It shows that compared with the AGA control, the ordinary sliding mode composite control reduces the overshoot effectively, indicating the effectivity of the sliding mode control.

Table 1 System simulation parameters

Parameters	Value	Parameters	Value
R_c [Ω]	0.13	P_{case} [Pa]	2×10^4
L_c [mH]	4.8	ξ [$m^3\cdot Pa\cdot s^{-1}$]	2×10^{-12}
C_E [$V\cdot s\cdot rad^{-1}$]	0.215	L_e [$m^3\cdot Pa\cdot s^{-1}$]	0.5×10^{-12}
C_t [$N\cdot m\cdot A^{-1}$]	0.179	E_y [$N\cdot m^{-2}$]	6.86×10^8
K_f [$N\cdot m\cdot rad\cdot s^{-1}$]	6×10^{-4}	A_t [m^2]	1.83×10^{-3}
Dp [10^{-7} m3$\cdot rad^{-1}$]	4.8	V_t [m^3]	1.5×10^{-4}
J_m [$kg\cdot m^2$]	1.49×10^{-3}	M [kg]	1.42
J_p [$kg\cdot m^2$]	1.2×10^{-4}	B_t [$N\cdot m\cdot s^{-1}$]	100

b. Sinusoidal response analysis.

The position command is $10\sin(2\pi ft)$mm, observe the tracking of input and output signals.

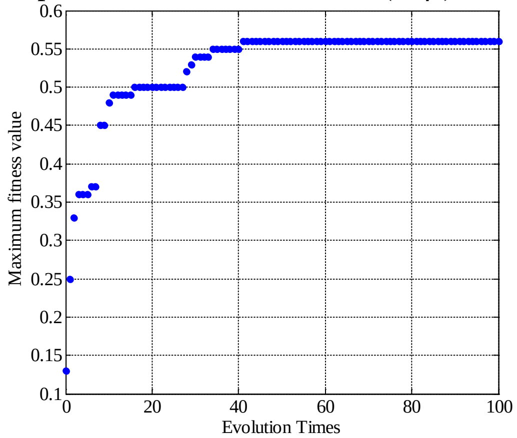


Fig. 3 The maximum fitness values change process

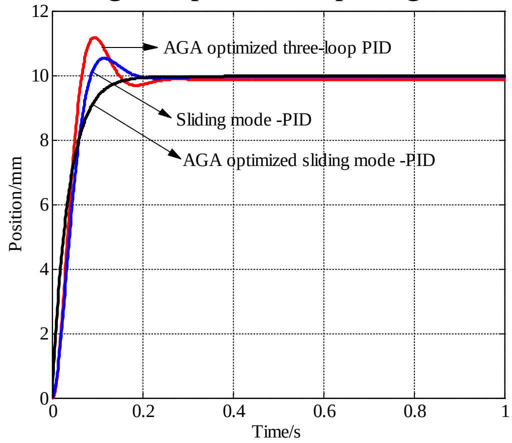
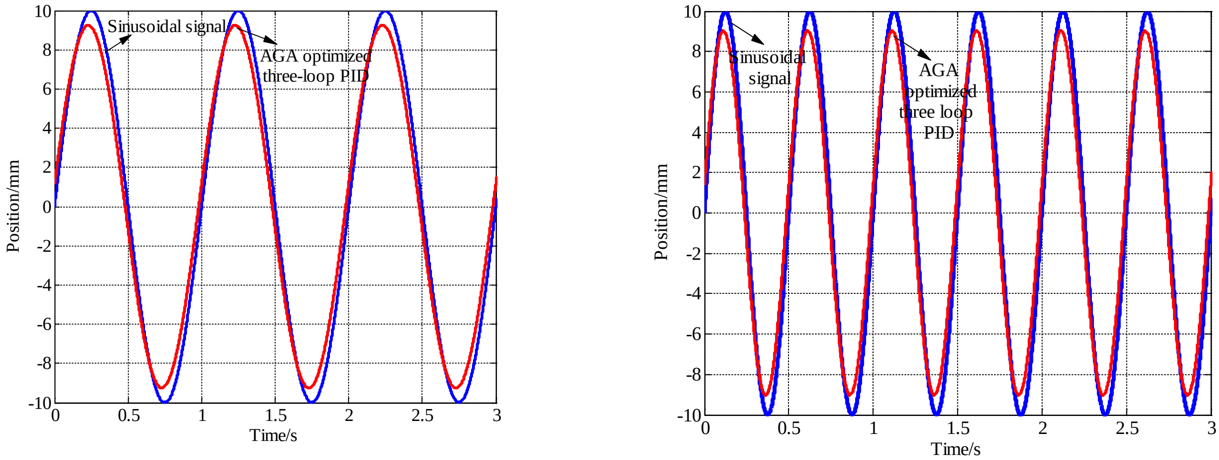


Fig. 4 EHA step response

Fig. 5 (a), (b) are sinusoidal responses of AGA optimized three-loop PID control at frequencies 1 Hz and 2 Hz. It shows that AGA control always has a distinct tracking error which can not be eliminated in the control process. As the frequency increases, the tracking error increases too.

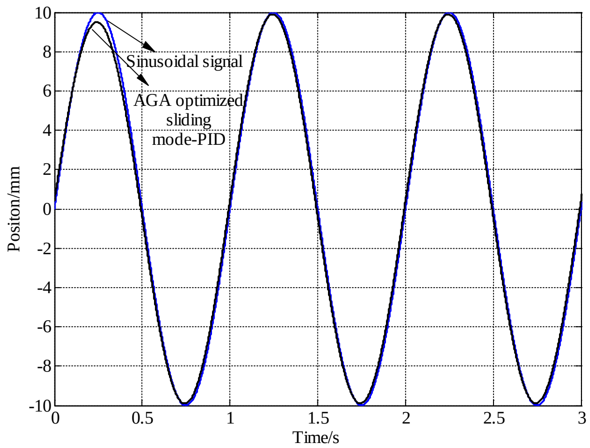


(a) 1Hz (b) 2Hz

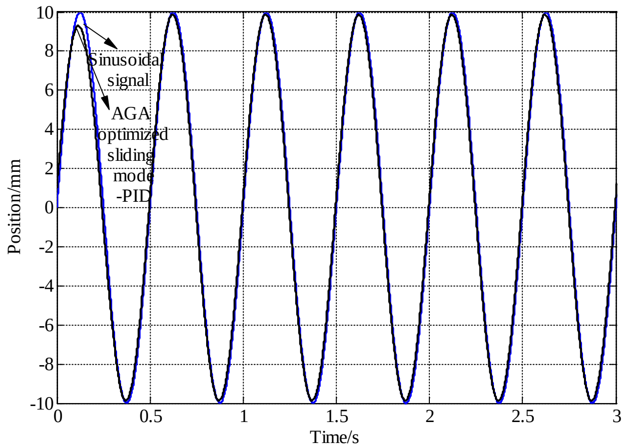
Fig. 5 Sinusoidal signal tracking curve of AGA optimized three-loop PID control

Fig. 6 (a), (b) are sinusoidal responses of AGA optimized sliding mode-PID composite control at frequencies 1 Hz and 2 Hz. It shows that AGA control has a slight initial amplitude attenuation, the sinusoidal signal can be basically tracked within 0.5s, the error is within 1.5%; At the frequency of 2 Hz, the system can basically track the sinusoidal signal in one cycle after the initial significant error.

This shows that the AGA optimized control can gradually reduce or eliminate the following error during the control process.



(a) 1Hz



(b) 2Hz

Fig. 6 Sinusoidal signal tracking curve of AGA optimized Sliding mode-PID composite control

Through the analysis of simulation results, the superiority of AGA-optimized sliding mode-PID composite control over AGA-optimized three-loop PID control is verified.

5. Summary

A sliding mode-PID composite control system is designed based on the ITAE index, the objective function and fitness function of the composite control parameter optimization are designed considering the rise time, control output and overshoot. Then adaptive genetic algorithm (AGA) is applied to optimize the control parameters, and achieve the synchronization between optimization and simulation by transferring the parameters between fitness function and Simulink simulation model. The simulation results verify the effectiveness of the proposed optimization control method and solve the problem that the simple PID control can not achieve the ideal control effect of the EHA nonlinear system.

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