The Research on EHA Based Aircraft Braking System and Its Nonlinear Control

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***Abstract*—An Electro-hydrostatic actuator (EHA) structure with joint of pump control and valve control is proposed for more electric aircraft (MEA) braking system, the working principle of the system is analyzed, and on the basis of that, the mathematical models of the system components are established. To compromise the problem of pressure overshoot and dynamic characteristics with the conventional PID control method, and to prevent wheels from mistakenly locking which resulting in decreased brake efficiency, a fuzzy PID pressure controller is designed. Through simulation test, the rated pressure step response time of the system is about 0.35 s with 2 percent overshoot and 0.05 MPa steady-state error, the system -3 dB bandwidth is 8 Hz. It is demonstrated that the structure is feasible, the controller design is reasonable, and the EHA can satisfy the requirements of the aircraft braking system in static and dynamic performance.**

Keywords-aircraft braking system; electro-hydrostatic actuator; antiskid control; fuzzy PID control

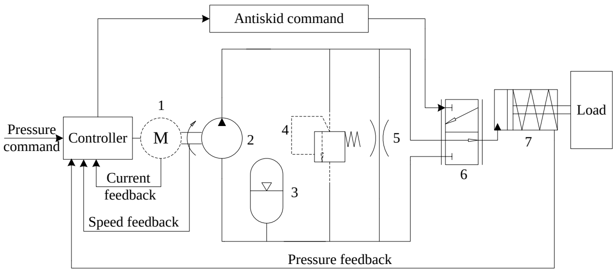
I. INTRODUCTION

Aircraft braking system is important aircraft airborne equipment, it is also a relatively independent functional subsystem. Currently, the electric braking technology is the development trend of the aircraft braking system[1], and there are two ways to achieve this technology: one is the use of electro-mechanical actuator (EMA) technology which is commonly called all-electric brakes, it has no hydraulic components and with the features of compactness, no oil and easy maintenance[2]. Another is the use of electro- hydrostatic actuator (EHA) technology which has no external hydraulic source, but comes with the motor, pump and hydraulic components which are all in one integrated package with the features of light weight and high reliability[3]. This technology can take advantages of both electronic and hydraulic systems, and has the capability of great braking torque, high accuracy and rapid response, so it is a promising brake technology.

Although EHA technology has been widely studied in the world, the reported literature basically confined to the rudder control mechanism in the flight control system[4-6], rarely research literatures are concerned with aircraft braking systems. Ref. [7] proposed an EHA based aircraft braking system structure, using two-way fixed-displacement piston pump and double-acting hydraulic cylinder to adjust the braking pressure and implement anti-skid function, but the moment of inertia of the motor and the pump itself limits the system dynamic performance. Consider the overall performance requirements, an EHA structure suitable for the special requirements of aircraft anti-skid braking system was proposed, the system mathematical models of various components were established, and to compromise the problem of pressure overshoot and dynamic characteristics with the conventional PID control method, a fuzzy PID pressure controller was designed, the simulation experiment was done and analyzed which verifies the feasibility of the proposed EHA structure for aircraft braking system.

II. THE STRUCTURE AND WORKING PRINCIPLE OF EHA

According to the frequency response requirements of the aircraft braking system, an electro-hydrostatic actuator structure with joint of pump control and valve control is proposed for aircraft braking system (Fig. 1). The system is composed of controller, brushless DC motor (BLDCM), one-way fixed-displacement piston pump, accumulator, relief valve, throttle valve, three-way directional valve, single-acting hydraulic cylinder, signal measuring device and other components.



1. Brushless DC motor, 2. One-way fixed-displacement piston pump,
3. Accumulator, 4. Relief valve, 5. Throttle valve,
6. Three-way directional valve, 7. Single-acting hydraulic cylinder.

Figure 1. Space vector diagram of IPMSM.

The brushless DC motor is used for efficiently driving the pump and is connected with the pump coaxially. The accumulator is used as a tank which provides initial inlet pressure for the pump, which can prevent cavitations and supplement the leakage of hydraulic oil, and can also improve the stiffness of the whole system. To ensure the safety of the system, a relief valve is set up to prevent system failure caused by excessive high pressure. The throttle valve and pump can produce some leakage, resulting in little loss of efficiency, so that the brushless DC motor can remain at a certain speed when the system has reached the set pressure, thus can improve the dynamic characteristics; Furthermore, when need to reduce the pressure, the throttle valve can provide part of the relief passage, thus can improve the system dynamic response. The three-way directional valve is used to achieve fast switching between pressure tracking and anti-skid braking. Just as the original hydraulic braking system, the actuation device is single-acting hydraulic cylinder, so we can achieve EHA based aircraft braking system with little modifications to the original hydraulic braking system.

The system runs in the mode of combination of pump control and valve control. According to the aircraft braking pressure requirements, the controller constitutes closed-loop control by adjusting the speed of brushless DC motor and pump based on the hydraulic pressure sensor, thus can control the pressure and flow of the pump, and reach the purpose of braking pressure regulation. Since the hydraulic piston requires frequent advance and retreat in the anti-skid braking process to achieve braking and anti-skid purpose, if pump control method is used by changing the rotation direction of the motor to make the hydraulic piston forward and back, as the motor and pump have considerable moment of inertia, it is difficult to meet the requirements of rapidly change between forward and reversal rotation for rapidity requirements of anti-skid brake. Therefore, in this paper, we propose the method of combination of pump control and valve control: by controlling the pump speed to adjust pressure and by using three-way directional valve to achieve the rapid conversion between braking and anti-skid braking.

The external input of the system is braking pressure command and the controller calculates the anti-skid command from it, the compositive braking pressure regulating signal is composed both of those. The system has two working status: pressurized braking status and anti-skid braking status. In pressurized braking status, the controller has pressure loop, speed loop and current loop control, the pressure of hydraulic cylinder is controlled at a given pressure value; In anti-skid braking status, the anti-skid command is given to three-way directional valve to make the hydraulic cylinder release the pressure quickly, thus anti-skid function can be achieved.

III. THE MATHEMATICAL MODEL OF EHA

In order to establish the overall mathematical model of EHA for aircraft braking system, we first analyze the mathematical model of several important elements.

A. Brushless DC motor

Brushless DC motor has the feature of small size, high efficiency and high reliability. It is the ideal motor for aircraft electric actuation systems[8]. Since the internal dynamics of brushless DC motor is not the emphasis of this paper, therefore, we can simplify the motor model as:

$$U = R_a I_a + L\frac{dI_a}{dt} + E_a \tag{1}$$

$$E_a = K_\omega \omega \tag{2}$$

$$T_e = k_T I_a \tag{3}$$

$$T_e - T_L = J\frac{d\Omega}{dt} \tag{4}$$

where U is the armature voltage, R_a is the armature resistance, I_a is the armature current, L is the armature winding inductance, E_a is the induced electro-motive force (EMF), K_ω is the EMF coefficient, k_T is the torque coefficient, ω is the electrical angular velocity, Ω is the mechanical angular velocity, T_e is the electromagnetic torque, T_L is the load torque, J is the moment of inertia of rotor.

It can be seen from Eq. (3) that the electromagnetic torque expression of the brushless DC motor is just like the DC motor. The electromagnetic torque is proportional to the amplitude of flux and current, so the torque of brushless DC motor can be controlled by controlling the amplitude of the inverter output square wave current.

B. One-way fixed-displacement piston pump

Piston pump is a kind of reciprocating pump which belongs to volume pump[9]. The EHA for aircraft braking system uses a small and fixed displacement, high speed one-way piston pump which can effectively reduce the size and weight of the system, the mathematical model is:

$$q = D\Omega - k_{leak} p \tag{5}$$

$$T = Dp / \eta_{mech} \tag{6}$$

$$\eta_{total} = \eta_{mech}\eta_V \tag{7}$$

$$k_{leak} = k_{HP} / v\rho \tag{8}$$

$$k_{HP} = \frac{D\Omega_{nom}(1-\eta_V)v_{nom}\rho}{p_{nom}} \tag{9}$$

$$p = p_P - p_T \tag{10}$$

where q is the flow, p is the differential pressure between outlet pressure and inlet pressure, p_P is the outlet pressure, p_T is the inlet pressure, T is the torque, D is the displacement, k_{leak} is the leakage coefficient, k_{HP} is the Hagen-Poiseuille coefficient, η_v is the volumetric efficiency, η_{mech} is the mechanical efficiency, η_{total} is the total efficiency, v is the kinematic viscosity of the fluid, ρ is the fluid density, p_{norm} is the rated pressure, Ω_{norm} is the rated angular velocity, v_{norm} is the nominal kinematic viscosity fluid.

C. Accumulator

In this system, the accumulator is used as a tank which provides initial inlet pressure for the pump, which can prevent cavitations and supplement the leakage of hydraulic oil, and can also improve the stiffness of the whole system. Currently, the most widely used accumulator is the inflatable type, including cylinder type, piston type and bladder type. They are all working in the principle of compressibility of hermetic gas[9]. The mathematical model of accumulator is:

$$q = \frac{dV_F}{dt} \tag{11}$$

$$V_F = \begin{cases} 0 & \text{for } p \le p_{pr} \\ V_A[1-(\frac{p_{pr}}{p})^{\frac{1}{k}}] & \text{for } p > p_{pr} \end{cases} \tag{12}$$

where V_F is the liquid volume, V_A is the accumulator volume, p is the inlet pressure, p_{pr} is the precharge pressure, k is the specific heat, q is the flow.

D. Throttle valve

The throttle valve works by changing the cross section or passing length to control the fluid flow. It is a simple flow control valve without feedback function, so it can not compensate the flow rate instability caused by load change. In this system, a fixed throttle with constant circulation area is used, in which the flow rate is only related to differential pressure. The mathematical model of throttle valve is:

$$q=\begin{cases} C_{\mathrm{D}}A\sqrt{\dfrac{2}{\rho}|p|}\cdot sign(p) & for\,\mathrm{Re}\geq \mathrm{Re}_{\mathrm{cr}} \\ 2C_{\mathrm{DL}}A\dfrac{D_{\mathrm{H}}}{v\rho}p & for\,\mathrm{Re}<\mathrm{Re}_{\mathrm{cr}} \end{cases} \tag{13}$$

$$p=p_{\mathrm{A}}-p_{\mathrm{B}} \tag{14}$$

$$\mathrm{Re}=\frac{qD_{\mathrm{H}}}{Av} \tag{15}$$

$$C_{\mathrm{DL}}=\left(\frac{C_{\mathrm{D}}}{\sqrt{\mathrm{Re}_{\mathrm{cr}}}}\right)^2 \tag{16}$$

$$D_{\mathrm{H}}=\sqrt{\frac{4A}{\pi}} \tag{17}$$

where q is the flow, p is the differential pressure, p_{A} and p_{B} are the port pressures, C_{D} is the flow leakage coefficient, A is the passing area, D_{H} is the passing diameter, ρ is the fluid density, v is the kinematic viscosity of the fluid.

E. Single-acting hydraulic cylinder

Hydraulic cylinder is widely used to achieve linear reciprocating motion, it has the feature of simple structure, easy to manufacture and high reliability. Single-acting hydraulic cylinder uses hydraulic pressure to push the piston toward one direction, while the reverse movement relies on gravity or spring force, etc. For the aircraft application occasions requiring small size, light weight and large output force, medium and high pressure hydraulic cylinders with rated pressure of 10 ~ 16 MPa are usually used. It should be noted that the current aircraft hydraulic braking system also uses a single-acting hydraulic cylinder, so it can facilitates the upgrading from traditional hydraulic braking system to EHA based braking system.

Ignore the fluid compressibility, friction and leakage, the mathematical model of single-acting hydraulic cylinder is:

$$F=Ap \tag{18}$$

$$q=Av+\frac{(V_0+Ax)}{\beta}\dot{p} \tag{19}$$

$$\frac{dx}{dt}=v \tag{20}$$

where F is the thrust on the piston, v is the piston speed, A is the piston area, p is the inlet pressure, q is the inlet flow, x is the piston displacement, V_0 is the average volume of hydraulic lines and hydraulic piston, β is the equivalent elastic modulus of hydraulic oil.

IV. PRESSURE CONTROLLER DESIGN

The proposed EHA system presents a strong nonlinear characteristic because of the flow nonlinearity of piston pump, throttle valve and hydraulic cylinder, the nonlinearity of strong coupled brushless DC motor control system, as well as the pipeline pressure losses, resistance losses along the way and local resistance losses, it is difficult for the conventional PID control method to achieve excellent control performances, the pressure overshoot and dynamic characteristics can not be easily compromised so as to make the system be prone to mistakenly hold the wheel death, thus resulting in the decline of braking efficiency. Therefore, by considering the practical engineering application, a fuzzy PID control method for EHA used for aircraft braking system is designed.

As shown in Fig. 2, the pressure loop of EHA for aircraft braking system is controlled by a fuzzy PID controller. The PID parameters are fuzzily tuned online by mainly using pressure deviation e and pressure deviation rate ec. The core idea is to identify the fuzzy relation between the three PID parameters and e , ec. In operation, the three PID parameters are adjusted online according to fuzzy control rule by continuously detecting e and ec, so that the controlled object has good static and dynamic performances with little computation quantity.

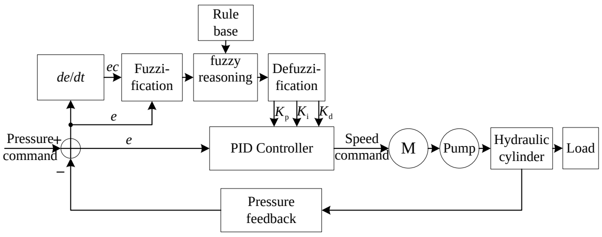


Figure 2. Fuzzy PID control block diagram for EHA.

The fuzzy control rules are obtained from a typical servo response curve. Each control rule is taken from a representative point in the response curve, such as the peak point or the intersection with the expected value. The design principle is: when the error is large, the change of control input should try to make the error decreases quickly; when the error is small, in addition to eliminate error, we should consider the stability of the system to prevent unnecessary system overshoot or even system oscillation. The fuzzy rule tables for K_{p}, K_{i}, K_{d} are shown in Table. 1, Table. 2 and Table. 3 respectively.

TABLE I. FUZZY RULE TABLE FOR K_{P}

ec e	NB	NS	ZO	PS	PB
NB	PB	PB	PB	PB	PB
NS	PB	PB	PB	PM	PS
NZ	PB	PB	PB	PS	ZO
PZ	ZO	PS	PB	PB	PB
PS	PS	PM	PB	PB	PB
PB	PB	PB	PB	PB	PB

TABLE II. FUZZY RULE TABLE FOR K_{I}

ec e	NB	NS	ZO	PS	PB
NB	ZO	ZO	ZO	ZO	ZO
NS	PM	PS	PS	PS	ZO
NZ	PB	PB	PB	PM	PS
PZ	PS	PM	PB	PB	PB
PS	ZO	PS	PS	PS	PM
PB	ZO	ZO	ZO	ZO	ZO

TABLE III. FUZZY RULE TABLE FOR K_{D}

ec e	NB	NS	ZO	PS	PB
NB	ZO	ZO	ZO	ZO	ZO
NS	ZO	PS	PM	PS	ZO
NZ	ZO	ZO	PS	ZO	ZO
PZ	ZO	ZO	PS	ZO	ZO
PS	ZO	PS	PM	PS	ZO
PB	ZO	ZO	ZO	ZO	ZO

Where e and ec are normalized fuzzy controller input variables, NB stands for negative big, NS stands for negative small, NZ stands for negative zero, PZ stands for positive zero, PS stands for positive small, PB stands for positive big, ZO stands for zero, NM stands for negative medium, PM stands for positive medium. De-fuzzy part adopts Mamnida reasoning, and uses gravity method to calculate the exact output amount of fuzzy control.

V. SIMULATION RESULTS AND ANALYSIS

Based on the above analysis, the mathematical model of EHA for aircraft braking system is established in Matlab/Simulink based on SimPowerSystems, SimHydraulics and SimMechanics, the simulation block diagram is shown in Fig. 3.

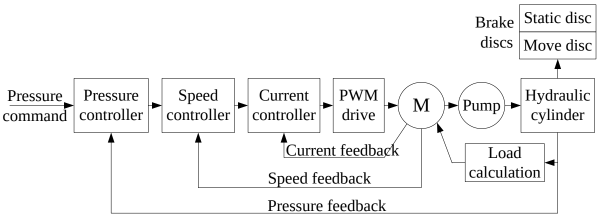
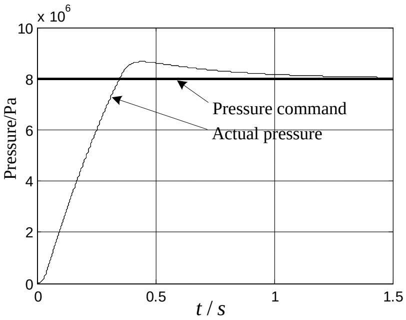


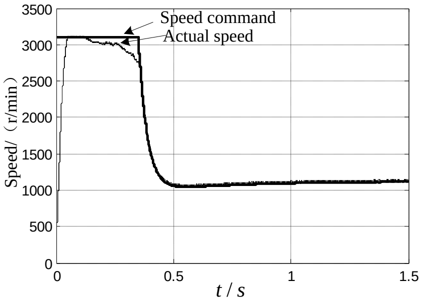
Figure 3. Simulation diagram for EHA.

The main parameters of various parts in EHA are as follows. The brushless DC motor: rated voltage 270 V, rated speed 3100 r/min, rated torque 1.5 N m, moment of inertia 1.2×10^{-4} kg.m^{2,} winding resistance 0.2 Ω, winding inductance 1.5 mH, number of pole pairs 2. The one-way fixed-displacement piston pump: displacement 0.139×10^{-6} m^3/rad, rated pressure 20 MPa, rated angular speed 325 rad/s, total efficiency 0.8, volumetric efficiency 0.92, mechanical efficiency 0.87. The throttle valve: diameter 0.002 m, flow leakage coefficient 0.7. The three-way directional valve: maximum flow area 1.0×10^{-5} m^2, maximum opening 0.005 m, leakage area 1.0×10^{-12} m^2. The single-acting hydraulic cylinder: piston area 1.25×10^{-3} m^2, piston stroke 0.005 m, stiffness 1.0×10^7 N/m, damper 150 N/(m/s). A PI controller is used for motor speed loop control with parameter of K_p=2, K_i=200. The control effects with conventional PID controller and the aforementioned fuzzy PID controller are compared in the following.

Fig. 4 shows the step response of EHA with conventional PID controller. Fig. 4 (a) is the pressure step response. If the pressure command is 8 MPa, the hydraulic cylinder pressure can track the given value at about 0.35 s with an overshoot of 8.6% and steady-state error of 0.08 MPa.



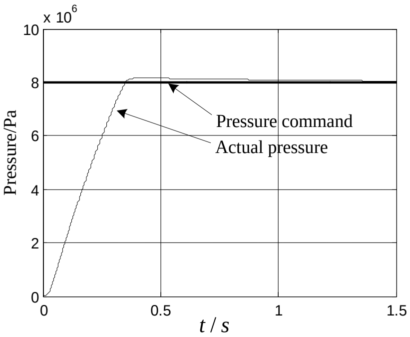
(a) Pressure



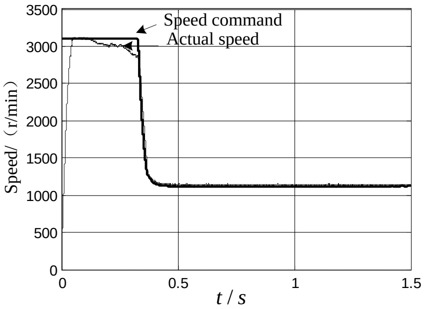
(b) Motor speed

Figure 4. Step response of EHA with conventional PID controller.

Fig. 5 shows the step response of EHA with the aforementioned fuzzy PID controller. Fig. 5 (a) is the pressure step response. If the pressure command is 8 MPa, the hydraulic cylinder pressure can track the given value at about 0.35 s with an overshoot of 2% and steady-state error of 0.05 MPa. Compared with conventional PID controller, it can be seen that the system has a higher steady-state performance that can effectively prevent mistakenly lock of wheels caused by pressure overshoot, thus can improve the braking efficiency. Fig. 5 (b) shows that after reaching the rated pressure, the motor speed can maintain at about 1100 r/min which is mainly caused by internal leakage of the throttle valve and pump, this verifies the foregoing analysis about the using of throttle valve. In addition, the speed of the brushless DC motor can track the speed command given by pressure loop controller quickly. Its dynamic performance is limited by the moment of inertia of motor and pump, the power level of motor, and the characteristics of motor controller.



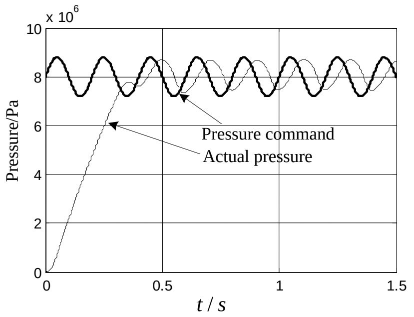
(a) Pressure



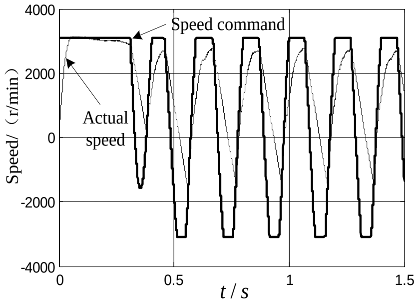
(b) Motor speed

Figure 5. Step response of EHA with fuzzy PID controller.

Fig. 6 shows the sinusoidal dynamic response of EHA. The pressure command is $8+0.8\sin(10\pi t)\ \text{(MPa)}$, it can be seen that the EHA can effectively track 5 Hz sinusoidal signal, thus the system can meet the requirements of aircraft braking system. Fig. 6 (b) shows that the motor may appear negative speed, at this time the pump is not working as a pump but as a hydraulic motor, that is, the pump now is a release passage in the pressure dynamic adjustment process, thus can increase the system frequency response. That's why there is not a check valve in the pump outlet. Through testing, the system -3 dB bandwidth is about 8 Hz, which can meet the requirements of aircraft braking system.



(a) Pressure



(b) Motor speed

Figure 6. Sinusoidal dynamic response of EHA.

VI. CONCLUSIONS

According to the frequency response requirements of the aircraft braking system, an electro-hydrostatic actuator structure with joint of pump control and valve control was proposed, and the controller with three control loops of pressure loop, speed loop and current loop was designed. The simulation was carried out and the results show that: the proposed structure of EHA is feasible and the controller design is reasonable, it can meet the requirements of aircraft braking system in static and dynamic performances. The research of this paper can provide a feasible reference for the design of actual EHA based aircraft braking system.

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