Design and simulation of hydraulic auto-brake-valve of unmanned aerial vehicle

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Abstract: This study designs one kind of hydraulic auto-brake-valve which calculates its driving force and velocity, simulates its braking force and stability, in order to accomplish auto brake in the landing condition and keep braking in cruising condition of the unmanned aerial vehicle. The auto-brake-valve uses a servo motor to drive lead screw and nut. The output pressure of the auto-brake-valve is changed by the variation of rotate speed and direction of servo motor, that can be completed the control of the brake device.

1 Overview

The aircraft braking system is an important braking device of modern aircraft. It can absorb the sliding kinetic energy of an aircraft during the landing and taxing stage. Speed the aircraft down rapidly. To shorten the running distance and ensure the aircraft stay. It is an important system to ensure the safe operation of aircraft. The way of aircraft brake is usually driven by hydraulic drive, all electric drive and electro-hydrostatic drive. The hydraulic driven brake system usually includes hydraulic power source, hydraulic brake valve, wheel brake device, operation and control system, etc. [1–4]. The brake valves for aircraft are mostly mechanical, control by hand or foot; the aircraft using this kind of brake valve can only realise the artificial brake [5]. In order to realise the function of remote control brake and automatic brake of the unmanned aerial vehicle (UAV), in this paper, a new type of hydraulic automatic brake valve is designed, and its key characteristics are simulated and tested.

The brake system of a certain type of aircraft is composed of a hydraulic automatic brake valve and a brake device installed on the wheel. The hydraulic automatic brake valve provides and controls the output brake pressure for the UAV brake system. Brake pressure drives a brake device to realise UAV automatic braking. The principle of hydraulic automatic brake valve is based on the pulse-width modulation (PWM) control technology. The PWM control technology is widely used in analogue circuit control because of its simple control, flexibility and good dynamic response. The flight control computer puts the PWM signal into the controller; the digital signal is processed and output by a microprocessor for analogue circuit control in order to control the forward, reverse or stop of motor components by change the output voltage of the analogue circuit. At the same time, the pressure sensor is used to collect the product pressure in real time, and the electrical signal to the microprocessor through the proportional–integral–derivative operation, to control the working state of the motor components to achieve the product output pressure and control signal linear corresponding control. During the working process of the motor assembly, in order to control the stroke of the motor assembly and ensure that the motor assembly will not overload and cannot be controlled normally at the beginning and the end of the stroke, Hall sensor is used to control the stroke of the motor assembly.

2 Overall design of hydraulic automatic brake valve

The schematic diagram of the operation principle of the hydraulic automatic brake valve is shown in Fig. 1. The hydraulic automatic brake valve adopts PWM signal input to design the controller. The controller controls the working state of the motor components according to the duty cycle ratio of the PWM signal to realise the forward, reverse or stop control of the motor components. The motor produces rotary motion to drive the ball nut to produce linear motion, compress the oil in the brake valve, and make the brake valve output corresponding pressure. When 0–100% PWM signal is input to the hydraulic automatic brake valve, the product can linearly output the hydraulic pressure corresponding to the control signal, and the output pressure can be linearly fed back by the electrical signal. When the PWM signal is 0%, the hydraulic automatic brake valve does not work, the output pressure is zero, and the brake device is in the state of releasing the brake; when the PWM signal increases from 0 to 100%, the output pressure of the hydraulic automatic brake valve gradually increases to the maximum, and the wheel brake is realised; when the control signal decreases from 100 to 0%, the brake pressure of the brake system gradually decreases, and the engine is realised Release the brake of the wheel.

The brake valve actuator is the key component of the hydraulic automatic brake valve, and its structure is shown in Fig. 2. The working process of the hydraulic automatic brake valve is to input PWM signal I1, compared the input signal I1 with the pressure signal I2 output by the pressure sensor at the output end of the brake valve, and feed the difference I=I1–I2 back to the servo motor controller. The controller generates the corresponding form and the size of motion according to the difference I=I1–I2 (when I1 > I2, i.e. I=I1–I2 > 0, the ball nut moves forward when I1 < I2, I=I1–I2 < 0, the ball nut moves backward and the output pressure continues to drop; when I1 = I2, I=I1–I2 = 0, the ball nut stops moving and the proportional output pressure does not change), the movement of the servo motor is transmitted to the brake valve actuator through the ball nut, the brake valve actuator compresses the hydraulic oil in the closed chamber to generate pressure, and the pressure is transmitted to the brake cylinder of the brake actuator through the conduit, the brake cylinder pushes the brake disc through the connecting rod. The output pressure electrical signal I2 of the pressure sensor at the output end of the brake valve changes with the change of the brake pressure. When the pressure value reaches the expected pressure value determined by the input signal I1, the output pressure signal I2 of the pressure sensor is equal to the input signal I1, and the difference I=I1–I2 is zero. At this time, the servo motor stops moving and the brake valve is in a static state. When the input signal I1 is changed, the difference signal I=I1–I2 will change, and the servo motor will...
follow the change of the difference signal \( I = i_1 - i_2 \). At this time, the brake pressure changes, and the output pressure electrical signal \( I_2 \) of the pressure sensor at the output end of the brake valve will also change with the change of the brake pressure until the difference signal \( I = i_1 - i_2 \) is zero again, and the brake valve reaches a new balance position.

### 3 Main parameters design of hydraulic automatic brake valve

#### 3.1 Calculation of driving force of hydraulic automatic brake valve

In the case of neglecting the friction resistance, the driving force can be calculated according to the following equation:

\[
F = F_1 + F_2 + F_3, \tag{1}
\]

where \( F_1 \) is the hydraulic pressure generated by an output pressure, N; \( F_2 \) is the maximum spring force produced by return spring, N; \( F_2 = 137 \) N; \( F_3 \) is the inertia force of screw nut, N; \( F_3 = 458 \) N.

\[
F_1 = \pi \times d^2 \times p, \tag{2}
\]

where \( d \) is the piston diameter of automatic brake valve, m, \( d = 2 \times 10^{-2} \) m, \( p \) is the maximum brake pressure of automatic brake valve, MPa, \( p = 6.5 \) MPa, so driving force: \( F = 2800 \) N.

#### 3.2 Calculation of piston moving speed

The movement of the piston causes the oil to move and compress in the closed chamber, which increases the oil pressure and produces the hydraulic brake force. The volume change of oil consists of three parts: the volume change of brake device, the volume change of brake valve, and the volume change of pipeline.

The relationship between the volume change of brake fluid and the pressure change is shown in the following equation:

\[
k = \frac{\Delta p_1}{\Delta V_1}, \tag{3}
\]

where \( k \) is the oil volume compression coefficient, MPa, MIL-PRF-83282 hydraulic oil, \( k = 800 \) MPa; \( \Delta p_1 \) is the maximum differential pressure before and after brake operation, MPa; \( \Delta p_1 = 6.5 \) MPa; \( V_i \) is the volume of initial fluid of brake device and pipeline, \( m^3 \); \( V_i = 50.24 \times 10^{-3} \) L; \( \Delta V_1 \) is the volume of fluid after brake compression, L, so \( \Delta V_1 = 0.408 \times 10^{-3} \) L.

The initial oil volume of brake valve is shown in the following formula:
$$V_z = \frac{\pi}{4} \times d^2 \times L_z,$$

(4)

where $V_z$ is the brake valve initial fluid volume, L; $L_z$ is the maximum stroke of the piston, $L_z = 18 \times 10^{-3}$ m, so $V_z = 5.65 \times 10^{-3}$ L.

The relationship between the change of brake valve fluid volume and the change of pressure can also be calculated by (3):

$$\Delta V_z = 0.0459 \times 10^{-3} L.$$

The hydraulic automatic brake valve and brake device of a UAV are connected by Teflon hose. The Teflon hose will deform and expand under pressure, and also produce volume change. The change volume caused by volume expansion can be calculated according to the following formula:

$$\Delta V_z = \beta \times L_z,$$

(5)

where $\beta$ is the coefficient of volume expansion of Teflon hose, mL/cm; $\beta = 0.00681$ mL/cm; $L_z$ is the piston stroke, m, so $\Delta V_z = 0.681 \times 10^{-3}$ L.

Therefore, during the braking process, the volume of the braking system changes is

$$V = \Delta V_z + V_z = (0.408 + 5.65 + 0.618) \times 10^{-3}$$

$$= 6.676 \times 10^{-3} L.$$

The movement speed of the piston can be calculated according to the following equation:

$$v = \frac{V}{(x/4) \times \frac{d}{r}},$$

(6)

where $t$ is the time for the brake valve to reach the maximum output pressure, s, $t = 2.05$ s, so $v = 10.38$ mm/s.

4 Simulation analysis of hydraulic automatic brake valve

4.1 Establish the mathematical model of servo motor speed control subsystem

In the hydraulic automatic brake valve, the motor is both the driving element and the control element. The mathematical model of the brushless DC motor is shown in the following equation:

$$\begin{align*}
U_c &= K_c \omega + L \frac{di}{dt} + R_i, \\
K_i &= J \omega + B_m \omega + T_1.
\end{align*}$$

(7)

where $U_c$ is the armature voltage; $V_c$; $K_c$ is the back EMF coefficient, V/(rad/s); $\omega$ is the motor output angular speed, rad/s; $L$ is the armature winding inductance, H; $i$ is the armature current, A; $R_i$ is the internal resistance of armature winding, $\Omega_i$, $K_i$ is the torque coefficient, N m/A; $J$ is the motor rotor moment of inertia, kg m$^2$; $B_m$ is the friction damping coefficient, N m/s/rad; $T_1$ is the load torque, N m.

4.2 Establish the mathematical model of screw nut subsystem

The rotation of the servo motor and the linear movement of screw nut can be calculated according to the following formula:

$$\frac{\omega_t}{\omega} = \frac{x_i}{L_z},$$

(8)

where $x_i$ is the axial displacement of the lead screw, m; $L_z$ is the axial displacement of nut, m.

In the case of axial load, the servo motor drives the lead screw to move, and the load torque of the servo motor $T_1$ is

$$T_1 = (T_{PL} + T_D + T_D) \frac{1}{\eta},$$

(9)

where

$$T_D = \frac{F_P V_D}{2 \pi \eta}, \quad T_{PL} = \frac{F_P L_P D}{2 \pi \eta} (1 - \eta).$$

The continuity equation of brake valve actuator and the force balance equation of piston rod is shown in the following equation:

$$\begin{align*}
\frac{\partial \rho}{\partial t} &= \frac{A_p}{\eta} (K_p \omega - A_p x - C_v \rho_l) \\
x = \frac{1}{m} (A_p \rho_l - B_c x - K x - F)
\end{align*}$$

(10)

where $\rho_l$ is the working pressure, Pa; $V_t$ is the control chamber volume, m$^3$; $K_p$ is the discharge coefficient, m$^3$/rad$^2$; $\gamma$ is the motor rotation angle, rad; $A_p$ is the effective area of brake valve actuator piston, m$^2$; $C_v$ is the leakage coefficient, m$^3$/(Pa s); $x$ is the piston rod displacement, m; $m$; $t$ is the total mass of the piston, kg; $B_c$ is the viscous damping coefficient, N s/m; $K$ is the brake disc load spring stiffness, N/m; $F$ is the brake disc load, N.

4.4 Simulation model and results

The simulation model of the hydraulic automatic brake valve is shown in Fig. 3. When a 100% duty cycle is input, the hydraulic pressure output by the brake valve is shown in Fig. 4, and the system can rise to the maximum pressure in about 0.2 S, and maintain stable output; when a 50% duty cycle is input, the hydraulic pressure output by the brake valve is shown in Fig. 5, and the system can rise to the maximum pressure in about 0.2 S, and maintain stable output; when 100% duty cycle is input, the maximum brake output with a 50% duty cycle is input. The pressure ratio is about 2, which can meet the linear output of brake pressure; when the corresponding duty cycle is input, when the brake pressure reaches the maximum, the hydraulic automatic brake valve can maintain the maximum output pressure, which can meet the braking requirements of the UAV in cruise state.

The open-loop Bode diagram of the hydraulic automatic brake valve is shown in Fig. 6. The amplitude crossing frequency of the system is 15.7 rad/s; the amplitude margin is 27.8 dB, phase crossing frequency is 0.645 rad/s, the phase angle margin is 54.7° and hydraulic automatic brake valve has good stability.

5 Conclusion

The hydraulic automatic brake valve has a simple structure, which can provide the wheel brake device with the liquid needed to generate the pressure and the brake pressure through the drive of the motor assembly; the hydraulic automatic brake valve has designed the oil storage cup, which has the ability of self-storing the working medium and can meet the use needs of the oil; in addition, according to the calculation and simulation results, the power consumption of the hydraulic automatic brake valve is relatively high small, fast response, fast, accurate and stable output of brake pressure within the specified time, the hydraulic automatic brake valve can meet the needs of use.
**Fig. 3**  
Simulation model of hydraulic automatic brake valve

**Fig. 4**  
Hydraulic pressure output by brake valve when a 100% duty cycle is input
Fig. 5 Hydraulic pressure output by brake valve when a 50% duty cycle is input

Fig. 6 Open-loop Bode diagram of hydraulic automatic brake valve

6 References
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