Research on Dual-Variable Integrated Electro-Hydrostatic Actuator

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Abstract: The integrated electro-hydrostatic actuator (EHA) with variable displacement and variable rotation speed is researched. In the system, the output of the actuator is changed by controlling the rotation speed of the brushless DC servomotor and the displacement of the servopump. The mathematical model described in state-space model is created. The system characteristics are studied based on the point of multiplicative dual-variable. And the basic method of control of the system is presented.

Key words: electro-hydrostatic actuator (EHA); power-by-wire (PBW); integrated; dual-variable control

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摘 要: 分析了变排量变转速型一体化电动静液作动系统, 通过同时控制直流无刷伺服电机转速和伺服泵排量达到改变作动器输出的目的, 并建立了其基于状态空间描述的数学模型, 根据其双变量相乘的特点对其系统特性进行研究, 提出了双变量一体化电动静液作动系统的基本控制方法。

关键词: 电动静液作动器(EHA); 功率电传(PBW); 一体化; 双变量控制
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The new type of power-by-wire actuator will be used in future airborne actuation system, such as the control system of the rudder. It includes Electro-Hydrostatic Actuator (EHA) and Electro-Mechanical Actuator (EMA), and it is one of the pivotal technologies of the More Electric Aircraft (MEA).

According to the differences of the types and control modes of the motor and the pump, there are three kinds of EHA, *i. e.*, EHA with fixed pump displacement and variable motor speed (EHA-FPVM), EHA with variable pump displacement and fixed motor speed (EHA-VPFM), and EHA with variable pump displacement and variable motor speed (EHA-VPVM)[1, 2].

The EHA uses a hydraulic pump to transfer the rotational motion of the electric motor to the actuator output. The hydraulic coupling allows a great deal of flexibility in the design of the actuator package. The locations and orientations of the motor and pump relative to the output cylinder can be readily varied to meet the package dimensional requirements. The EHA can also vary the transmission ratio by varying the displacement of the pump. The variable transmission ratio can be used to increase the actuator stiffness, decrease the package size, and decrease the package heating.

1 Creation of the System Mathematical Model

The EHA-VPVM system means that a variable speed brushless DC motor (BLDCM) is used to drive a variable displacement servopump, and the motor speed and the pump displacement can be varied synchronously as two system variables. By this means, it is capable to control the actuator output and the deflection angle of the rudder.

1.1 Model of the BLDCM

A BLDCM is used as the driving motor of the system, and its maximum speed is 12 000 r/min,

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nominal voltage is 270 V, and nominal power is 7.5 kW. The mathematical model of the BLDCM is created against the square-wave motor. The electromotive force balance equation is[3]

$$U_C = E + R_C i_C + L_C \frac{di_C}{dt} \tag{1}$$

The torques which act on the motor shaft are the electromagnetism torque and the load torque. And the torque balance equation of the BLDCM is

$$T_m = T_M + (J_m + J_p)\frac{d\omega}{dt} + (B_m + B_p)\omega \tag{2}$$

And the back electromotive force equation and electromagnetism torque equation are, respectively,

$$E = C_e \omega \tag{3}$$

and

$$T_m = C_m i_C \tag{4}$$

So it can be gotten that

$$U_C = C_e\omega + R_C i_C + L_C \frac{di_C}{dt} \tag{5}$$

With the Laplace transform, the motor speed can be gotten from Eqs. (1)-(4),

$$\omega(s) = \frac{C_m}{(L_C s + R_C)(J_M s + B_m) + C_e C_m} \cdot \tag{6}$$

$$U_C(s) - \frac{1}{J_M s + B_M + \dfrac{C_e C_m}{L_C s + R_C}} T_M$$

where ω is the rotation speed of the BLDCM, R_C is the motor winding resistance; L_C is the motor winding inductance; $J_M = J_m + J_p$ is the sum moment of inertia of motor and pump; $B_M = B_m + B_p$ is the sum damp coefficient of motor and pump; C_m is the electromagnetism torque constant; C_e is the back electromotive force constant; T_m is the electromagnetism torque, and T_M is the load torque which acts on the motor shaft, and can be described as

$$T_M = \frac{q_b p_f}{2\pi} \tag{7}$$

1.2 Model of the electrically driven variable displacement servo pump

Most traditional servo pumps have a variable displacement actuate unit driven by hydraulic servo system, and an actuator which is controlled by a servo valve to drive the swash plate of the pump. The fluid of the hydraulic servo system is supplied by the servo pump directly or by a small pump which is coaxial with the servo pump. This method has mature technology by which a rapid response can be achieved, but the additory hydraulic executive mechanism is complicated, and an exact servo valve is adopted, so the system failure rate is higher.

Because there is no constant system pressure in EHA, another way must be taken to provide the driving force for variable displacement mechanism. With the development of the motor, the servo motor has had a better performance, and its output power and response characteristics can meet some high requirement. For example, a kind of direct driven valve has been designed with a servo motor which replaces the valve's prestage. Based on these technologies, the design idea of Electrically Driven Variable Displacement Servo Pump is brought forward. A DC servo motor is introduced to drive the variable displacement mechanism *via* the driving gear. By this means the displacement of the pump can be varied to control the output flow of the EHA.

The theoretical output flow of the variable displacement pump is

$$Q_f(s) = \frac{K_Q \omega \gamma(s)}{2\pi} \tag{8}$$

where $q_b = K_Q \gamma$ is the displacement of the pump, and ω is the rotation speed of the motor-pump's main shaft.

A DC coreless servomotor is selected as the variable displacement actuating unit. Based on the electromotive force balance equation, torque balance equation, back-EMF equation and electromagnetism torque equation, and considering the load torque M_{Lb} as an external interfere, the armature voltage U_b as an input quantity, and the motor rev ω_b as an output quantity, and taking the inertia load and damping load into account at the same time, the transfer function of the DC servomotor which drives the swash plate can be gotten,

$$G_{\omega_b} = \frac{\omega_b(s)}{U_b(s)} = -\frac{C_{mb}}{C_{eb}C_{mb} + (J_b s + B_b)(L_{ab}s + R_{ab})} \quad (9)$$

The driving torques of the swash plate include the hydraulic torque of the plunger piston, the inertia torque of the plunger piston, the friction torque from the deflecting of the slipper and the friction torque from the fulcrum bearing of the swash plate. It is a function of rotation speed ω of the motor-pump's main shaft, the swivel angle γ of the swash plate, and the output pressure p_f of the pump. As γ is of small value, it can be considered that $\cos\gamma \approx 1$ and $\tan\gamma \approx \gamma$. So the driving torque M_Σ of the swash plate is

$$M_\Sigma = -K_a p_f - K_b \omega^2 \gamma \pm K_c p_f \quad (10)$$

where the negative sign means the torque increases the swivel angle of the swash plate. And in the present design of the Electrically Driven Variable Displacement Servo Pump, the following values can be gotten, $K_a = 5.9 \times 10^{-8}\ \mathrm{m}^3$, $K_b = 4.6 \times 10^{-6}\ \mathrm{kg \cdot m^2}$ and $K_c = 4.6 \times 10^{-8}\ \mathrm{m}^3$.

The reduction ratio of the driving mechanism of the swash plate is K_j, so the load torque which the driving mechanism of the swash plate acts on the servomotor shaft is $M_{Lb} = M_\Sigma / K_j$. From Eq. (10), the following equation can be gotten

$$M_{Lb} = \frac{-\operatorname{sign}(\gamma) K_a |p_f| - K_b \omega^2 \gamma + \operatorname{sign}(\omega_b) K_c |p_f|}{K_j} \quad (11)$$

The swivel angle of the swash plate is

$$\gamma(s) = \frac{\omega_b(s)}{K_j s} \quad (12)$$

The control mode of the servomotor is a dual closed loop mode. The current feedback constant is K_{I_b}, the speed feedback constant is K_{ω_b}, and the feedback constant of whole position loop is K_γ.

1.3 Model of the hydraulic system

Flow Q_f from the pump to the hydraulic system will drive the piston of the actuator; in addition, it will compensate the leakage of the actuator, the reduction of the oil, the expanding of the pipe and the actuation. So, the flow equation of the actuator is

$$Q_f = A\frac{dx_t}{dt} + \frac{V}{2E_y}\frac{dp_f}{dt} + C_{tg} p_f \quad (13)$$

where $C_{tg} = C_{ig} + C_{eg}$ is the leakage constant, C_{ig} is the inner leakage constant, C_{eg} is the outer leakage constant, V is the one-sided average volume of the pipe and actuator, and x_t is the position of the piston.

Load force balance equation of the actuator is

$$A p_f = m_t \frac{d^2 x_t}{dt^2} + B_t \frac{dx_t}{dt} + K_t x_t + F_L \quad (14)$$

where p_f is the load pressure, A is the piston area of the actuator, E_y is the modulus of volume elasticity of the oil, B_t is the viscous damping coefficient, K_t is the load elastic stiffness, F_L is the outer load force, and m_t is the mass of the piston[4].

1.4 Model of the load of the actuator

The rudder is hinged to the piston, the length of the hinge bar is R_h, and the dynamics equation of the rudder is

$$F_L R_h - \tau_L = (J_L s^2 + B_L s)\theta_L \quad (15)$$

where $\theta_L = x_t / R_h$ is the deflection angle of the rudder.

For a modern fighter plane with a stabilator, its hinge moment coefficient is $Ch_\alpha \approx Ch_\sigma$. So, the hinge moment of the rudder can be calculated with the equation

$$\tau_L = \bar{q} S_t R_h Ch_\sigma \left[\frac{\alpha(s)}{\theta_L(s)} + 1\right]\theta_L \quad (16)$$

where S_t is the area of the rudder, $\bar{q}$ is the dynamic pressure, Ch_α and Ch_σ are the hinge moment coefficients of the rudder relative to the angle of attack α and the deflection angle of the rudder θ_L.

This equation can be predigested as $\tau_L = G_\theta \theta_L$, and the G_θ has different values in different flight conditions.

1.5 Schematic block diagram of the total system

Based on the above analyses, the model of the dual-variable EHA system without controller can be gotten. The schematic block diagram is shown as Fig. 1.

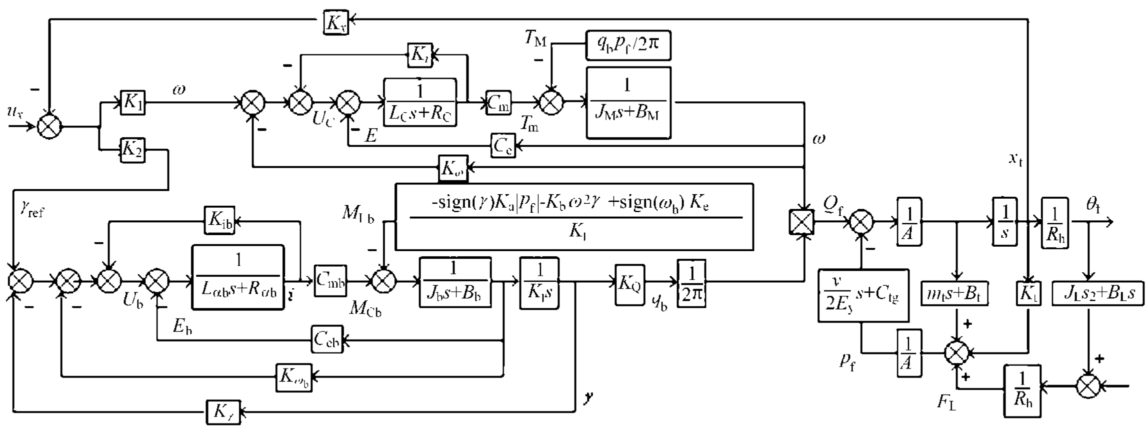

Fig. 1 Model of EHA-VPVM

1.6 State space model of the system

The EHA-VPVM system is a time invariant system with the single input and single output. The preset input value is $u = u_x$, and the output value is $y = \theta_L$, the deflection angle of the rudder. Taking the state variable as, $\boldsymbol{x} = [i_C \quad \omega \quad i_{Cb} \quad \omega_b \quad \gamma \quad p_f \quad x_t \quad \dot{x}_t]^T$, the system state equation $\dot{\boldsymbol{x}} = f(\boldsymbol{x})$ without input, i. e., $u = 0$, can be described as

$$\left.\begin{aligned}
\dot{x}_1 &= -\frac{R_C}{L_C} i_C - \frac{C_e}{L_C}\omega \\
\dot{x}_2 &= \frac{C_m}{J_M} i_C - \frac{B_M}{J_M}\omega - \frac{T_M(\boldsymbol{x})}{J_M} \\
\dot{x}_3 &= -\frac{R_{ab}}{L_{ab}} i_{Cb} - \frac{C_{eb}}{L_{ab}}\omega_b \\
\dot{x}_4 &= \frac{C_{mb}}{J_b} i_{Cb} - \frac{B_b}{J_b}\omega_b - \frac{M_{Lb}(\boldsymbol{x})}{J_b} \\
\dot{x}_5 &= \frac{1}{K_j}\omega_b \\
\dot{x}_6 &= \frac{K_Q E_y}{\pi V}\omega\gamma - \frac{2E_y C_{tg}}{V} p_f - \frac{2E_y A}{V}\dot{x}_t \\
\dot{x}_7 &= \dot{x}_t \\
\dot{x}_8 &= \frac{\left[A p_f - K_t x_t - \left(B_t + \frac{B_L}{R_h^2}\right)\dot{x}_t - \frac{\tau_L(\boldsymbol{x})}{R_h}\right]}{m_t + J_L/R_h^2}
\end{aligned}\right\} \tag{17}$$

where $T_M(\boldsymbol{x})$, $M_{Lb}(\boldsymbol{x})$ and $\tau_L(\boldsymbol{x})$ are shown as Eq. (7), Eq. (11) and Eq. (16), respectively.

2 Analysis of the Control Method

In the balance state, there is $\dot{\boldsymbol{x}} = f(\boldsymbol{x}) = \boldsymbol{0}$. So, from Eq. (17), it can be known that the system flow should be $Q_{f0} = \frac{K_Q \gamma_0 \omega_0}{2\pi} = 0$. It means that at least one of the rotation speed of the BLDCM ω and the displacement of the pump q_b should be zero, so that the balance state of the system can be gotten, $\boldsymbol{x}_0 = [0 \quad \omega_0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0]^T$ or $\boldsymbol{x}_0 = [0 \quad 0 \quad 0 \quad 0 \quad \gamma_0 \quad 0 \quad 0 \quad 0]^T$. The former state can be regarded as the EHA-VPFM, and the later state can be regarded as the EHA-FPVM. So, when having formed the closed loop K_γ of the swivel angle of the pump and the closed loop K_ω, the controllers of the BLDCM and servopump can be designed respectively.

From the schematic block diagram of the EHA-VPVM, it can be learned that the two controlled variables, the speed of the motor-pump ω and the displacement of the pump q_b, bring a nonlinearity of multiplication to the system. Fixing one of the two variables and varying the other, the system output can also be controled. The output of the system is a function of the square of the preset input value u_x. It means that the transfer function of the system is a kind of $G(s) = x_t/u_x^2$. At the same time, the preset values of the two controlled variables are gotten from the error of the position feedback.

High speed servomotor will have crawling and vibration in low speed state. So its low speed performance is limited, and there is a minimum rotation speed ω_{min}. To a BLDCM, it is more difficult to change its rotation direction than to a normal servomotor. And the system response characteristic will be reduced badly if the BLDCM changes its rotation direction continually around zero speed. If the dual-variable control mode is introduced, it is capable to control the motor to work in a right range of rotation speed, and vary the displacement of the pump to meet the requirement of varying the system flow. So, the requirement of the motor's low speed performance is reduced. In the EHA-FPVM system, the BLDCM should reach a low speed of about 1 rad/s to compensate the flow loss which comes from the leakage. It is unrealistic for a BLDCM driven by square-wave.

The efficiency and heat dissipation are significant problems in airborne actuation system. In the EHA system, the main consideration is focused on the motor efficiencies. Motor has different efficiencies under different speeds and torques. So, it is capable to vary the pump displacement to let the motor work on higher efficiency operating point.

The output torque of the motor is proportional to the current. Furthermore, the output torque depends on the load pressure and the pump displacement. So, it is capable to match the pump displacement and motor speed to keep the suitable speed of the actuator in a specified load state. As in a high load (high p_f) and low speed (low Q_f) state, it is capable to reduce the pump displacement q_f and increase the motor speed ω, and keep the output power. By this way, the torque of the motor is reduced, and the working current is reduced too. So, the I^2R loss is limited and the heat dissipation of the motor is reduced. The motor will work efficiently.

In Ref. [6], a kind of control method is introduced. A functional switch which can change the control signal is employed to switch between the motor speed controlling and pump displacement controlling. Through this way, the low speed state and low efficiency state of the motor can be avoided, and 20% power cost is cut down.

A simulation model of EHA-VPVM system is created in Simulink/Matlab. And a fuzzy controller is introduced as the controller of the outer loop of the system. The control laws are created based on the above analyses. The control structure is shown as Fig. 2. The step response curves of variable displacement controlling, variable speed controlling and dual-variable controlling are shown as Fig. 3. In the simulation, the BLDCM speed is limited to 1 000-10 000 r/min, and the direction of rotation is fixed. Simulation results show that the dual-variable control method is feasible. But the dynamic response characteristic and control precision require improvement, and further study for the control method is hoped. At the same time, it can be learned that when dual-variable control is introduced, the system response characteristic lies on the slower one of the displacement controlling and rotation speed controlling.

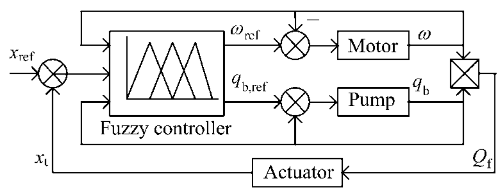

Fig. 2 Control structure of dual-variable system

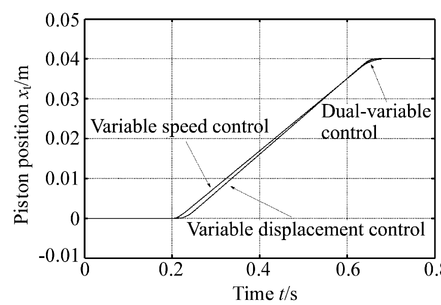

Fig. 3 The step response curves of the system under different control modes

3 Conclusion

The dual-variable EHA is a new concept of the actuation system. And it is in theory studying step no matter overseas or inland. In the study presented here, the mathematical model described in state-space model is created; the nonlinearity of dual-variable multiplicative and the effects on the system coming from the dual-variable are analyzed. A kind of basic control method for EHA-VPVM is presented. But the detailed control method is waiting for further studying. And it is needed to found a schematic prototype. This work is on its way.

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