A NOVEL ELECTRICAL SERVO VARIABLE DISPLACEMENT HYDRAULIC PUMP USED FOR INTEGRATED ACTUATOR IN MEA

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Abstract

The More Electric Aircrafts(MEAs) *such as A380 and B787 apply the Electro-Hydrostatic Actuator (EHA)/ Electro-Mechanical Actuator (EMA)/ Electrical Back-up Hydrostatic Actuator (EBHA) to drive the flight control actuations surfaces.Now the PBW actuators have been widely applied into more control surfaces. Such kinds of actuators have shown very good advantages. Next generation aircrafts will use more EHA and EMA. EHA requires the servo motor and servo pump for high performances. Among many kinds of EHAs, the EHA-Variable-displacement Pump(VP) is of its better characteristics. In this paper, an electrical servo variable pump is developed for EHA, and the adapted electrical variable servo mechanism is designed. Simulation and analysis show that this kind of servo pump is of very good performances that suited for Power-By-Wire(PBW)actuators. In the end, the experiment results are given and compared with theoretical one. It is indicated that this electrical servo variable pump has a good prospect of application.*

1 General Introduction

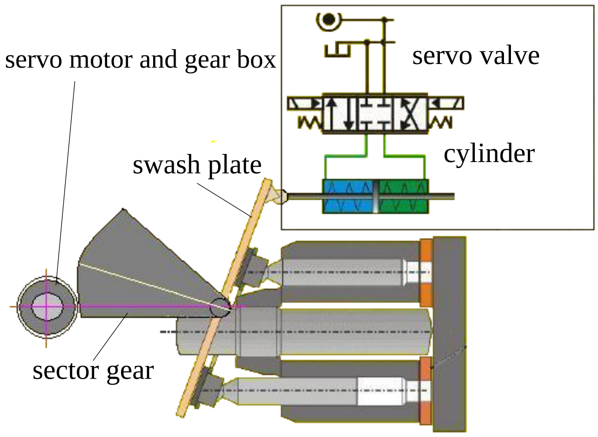
EHA is one development directions of the PBW actuators, one of the key sub-technologies of MEA, and the main way of the new aircraft actuating systems. EHA is one of volume control methods that means varying the system flow by controlling the speed of the motor and the displacement of the pump in the integrated hydraulic system and thus controls the output of the actuator. Based on the differences in the electric motors, pumps and control methods, EHA can be divided into three types, which are fixed displacement variable speed(EHA-FPVM), variable displacement fixed speed(EHA-VPFM) and variable displacement variable speed (EHA-VPVM).

By using dual-variable control, EHA-VPVM regulates the speed of the motor and the displacement of the pump at the same time, which increases a regulating freedom apiece compared to EHA-FPVM and EHA-VPFM that's why it comes true that the power of the motor exactly matches the system requirements, and improves the rigidity of the system and makes the performance of the system better[1~4].The method not only improves dynamic performance of the system but also reduces the heat.

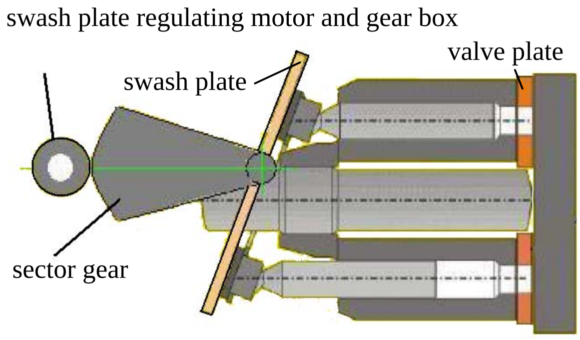
Direct-axis axial plunger pump varies the output flow with regulating the angle of inclination of the swash plate by the pump variable institutions. The actuating part of the variable displacement mechanism in conventional servo pump is mostly driven by hydraulic servo system, which controls a hydraulic cylinder to drive the variable displacement mechanism and regulate the displacement of the pump. The working fluid of the variable displacement mechanism is provided by either the hydraulic system directly or a small pump coaxial with the variable pump. This way is technically more mature, and has a good response performance, however, the complex structure of the additional hydraulic actuator and the introduced sophisticated servo valve link increase the failure rate and losses of the system. The system pressure and motor speed of the EHA are not constant, so the driving force of the variable displacement mechanism must be provided another way. With the development of motor technology, the performance of servo motor has been greatly improved; the output power and response characteristics of servo motors can meet the demand in some low-power high-performance applications. In this paper, an electric variable servo pump was developed to resolve those contradictions above, which drive the variable displacement mechanism of the servo pump by a DC servo motor through a gear transmission to provide a strong guarantee to EHA-VPVM.

2 Structure Design

The electric servo variable displacement pump uses a high-precision gear which is driven by a DC servo motor to regulate the swing angle of the swash plate in the variable plunger pump and thus the displacement varies. The method actualizes a variable displacement servo drive without servo valves, the structure is shown in Figure 1[5~6].



A）Contrast Between New And Traditional Design



B）Schematic of New Design

Fig.1. Schematic of Electric Variable Servo Pump

The actuating part of the variable displacement mechanism in conventional servo pump is a reciprocating hydraulic cylinder, which drive the swash plate to regulate the displacement with the moment arm. The servo valve and the cylinder are installed within the pump housing. The power density of the electric actuator is much smaller than the hydraulic actuator, therefore it is very difficult to place the variable mechanism within the pump housing. By using the rotary motor, the rotary motion of the motor can directly drive the swash plate with decelerating gear instead of converting into linear motion, thereby we can avoid the problems brought about by the hinging of the two ends of the actuating mechanism while the perpendicular displacement of the swash plate changing with the actuating mechanism moving straightly.

Therefore, the body of the variable displacement pump is reconstructed by using the actuating mechanism to drive the swing shaft of the swash plate directly through a sector gear instead of the servo valve and cylinder, shown in Figure 1. The sector gear locates outside the pump housing, and is rigidly coaxial with the swash plate. With the high-performance drag-cup DC servo motor and the matched integrated gearbox module, the deceleration of the motor is considerable, and the size of the variable mechanism is reduced. The structure is shown in Figure 2.

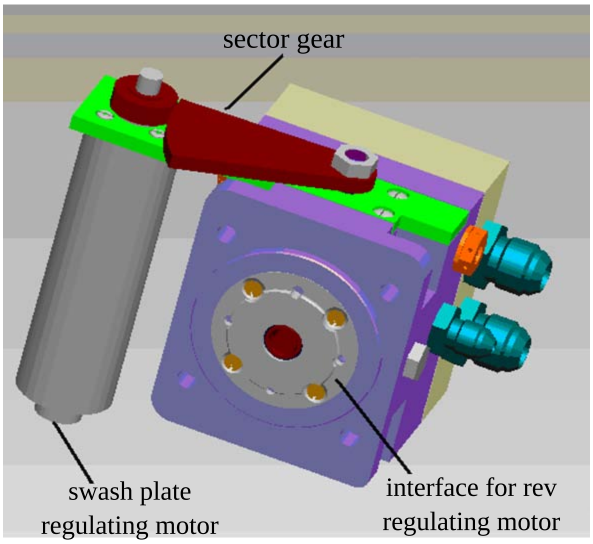


Fig.2. Three-dimensional Structure Diagram of The Electric Variable Servo Pump

3 Modeling and Simulation Analysis of The Variable Mechanism

Considering the inertia load and damping load, the open-loop transfer function of the DC servo motor that drives the swash plate is[7] as below according to the potential balance equation, the torque balance equation, EMF equation and the electromagnetic torque equation[9] , subjected to the load torque M_{Lb} as a external interference of the system, armature voltage U_b as the input, the motor speed ω_b as the output

$$\frac{\omega_b(s)}{U_b(s)} = \frac{C_{mb}}{C_{eb}C_{mb} + (J_b s + B_b)(L_{ab}s + R_{ab})} \quad (1)$$

in which U_b is the control voltage (V) , I_b is the armature current (A), R_{ab} is the armature resistance (Ω), L_{ab} is the armature inductance (H), E_b is the back EMF of the armature winding (V), J_b is the equivalent rotating inertia to the motor shaft (kgm2), C_{eb} is the back EMF constant (Vrad^{-1}s^{-1}), C_{mb} is the electromagnetic torque constant (Nm/A), B_b is the load damping coefficient, $T_{lb} = L_{ab} / R_{ab}$ is the electromagnetic time constant.

The total reduction ratio of the gearbox and the sector gear in the swing angle driving mechanism of the swash plate is K_j , then the angle of the swash plate is

$$\gamma(s) = \frac{\omega_b(s)}{K_j s} \quad (2)$$

The load torque M_{Lb} on the motor by the swash plate is

$$M_{Lb} = \frac{M_b}{K_j} \quad (3)$$

The theoretical displacement of the variable displacement pump q_b is

$$q_b = K_Q \gamma \quad (4)$$

The output flow $Q_f(s)$ is

$$Q_f(s) = K_Q \omega\gamma(s) / 2\pi \quad (5)$$

In which K_Q is the flow coefficient of the pump and ω is the shaft speed of the pump (rad/s).

The motor is controlled by a double closed loop with current feedback K_{ib} and speed feedback $K_{\omega b}$, so the whole position loop feedback is K_γ . The model is established as shown in Figure 3.

Subjected to the torque of the swash plate as an external interference, the open-loop transfer function is

$$G_b(s) = \frac{q_b}{U_b} = \frac{C_{mb}}{C_{eb}C_{mb} + (J_b s + B_b)(L_{ab}s + R_{ab})} \cdot \frac{K_Q}{K_j s} \quad (6)$$

in which there is an integral, it is a type I system.

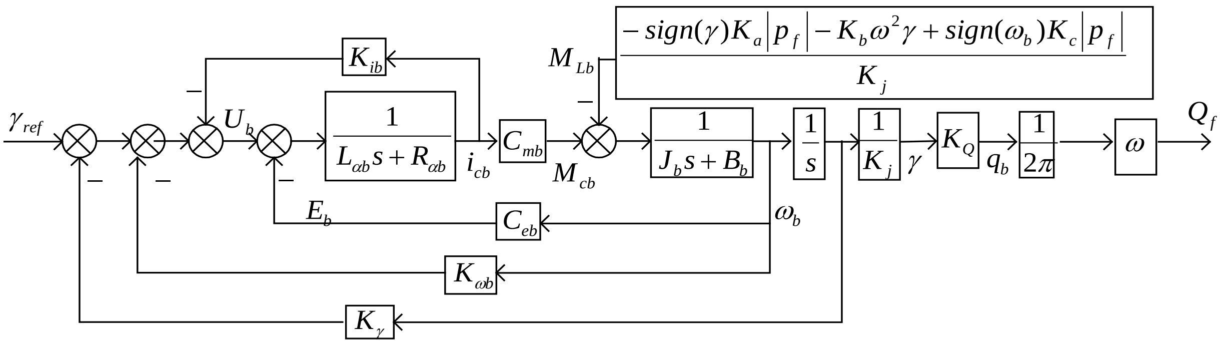


Fig.3. The Block Diagram of The Electric Variable Servo Pump System

The mathematical model above is simulated in MATLAB/Simulink. The maximum displacement of the variable pump is 2.5ml/r, the maximum speed is 10000rpm, the swing angle range of the swash plate is±15, the power of the DC servo motor driving the swash plate is 85W, and the rated speed is 5000rpm.

By ignoring the nonlinear components in the system, the result of the linear analysis, the open-loop and closed loop Bode plots of the electric servo variable pump, are shown in Figure 4. The phase margin of the open-loop is 89.6º, and the crossover frequency ω_c is 0.707Hz, which is far less than the corner frequency point, thus the system has a larger stability margin. According to the simulation results we can increase the open-loop amplification to improve the cutoff frequency, thereby improving the rapidity.

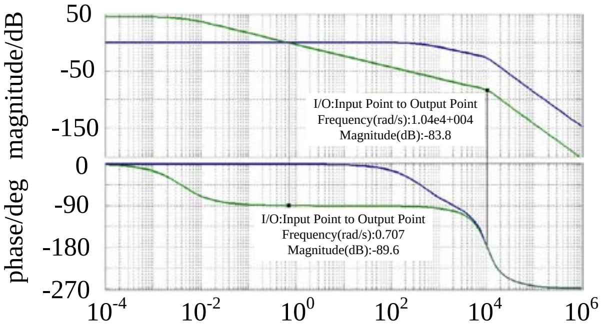


Fig.4. the Open-Loop and Closed Loop Bode Plots of The Electric Servo Variable Pump

Because of the nonlinear components such as the saturation voltage, the saturation current, the friction, the clearance and the dead zone, the linear analysis of the system is not enough. Then we use a PID controller to control the external ring swing angle with a PI controller in the inner loop, the step response at the maximum load without an overshoot is shown in Figure 5. The response of small-signal sinusoidal input is shown in Figure 6, the given amplitude is 0.75°, the frequency is 15Hz, and the response of the swash plate is 0.702°, which can meet the requirements of the frequency response in the EHA system.

The simulations results show that the output displacement of the designed servo pump can be regulated rapidly without overshoot, the settling time and the frequency response of small-signal can meet the requirements.

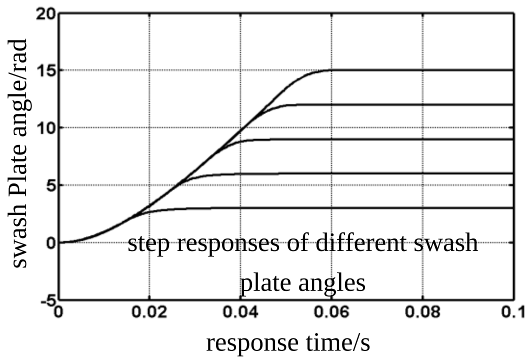


Fig.5. Series of Step Responses

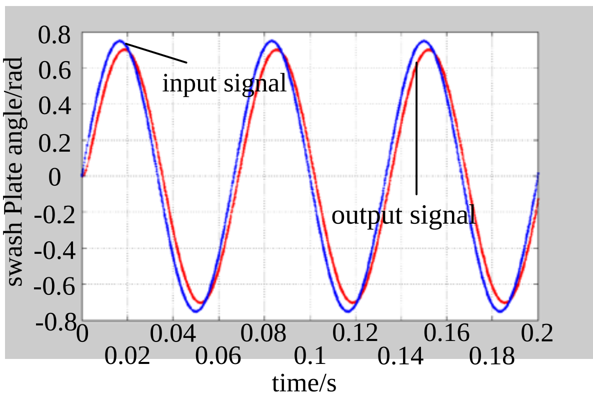


Fig.6. 5% Small Signal Frequency Response @15Hz

4 Experiments

The developed variable electric servo axial plunger pump and the hydraulic system test-bed are shown in Figure 7 and Figure 8 respectively.

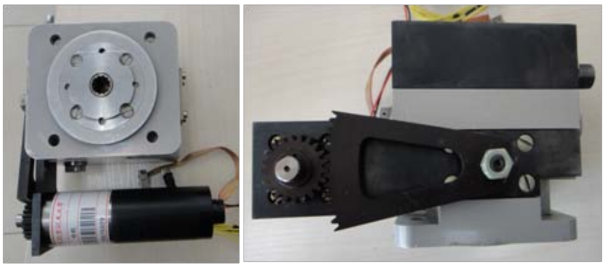


Fig.7 Photos of The Pump

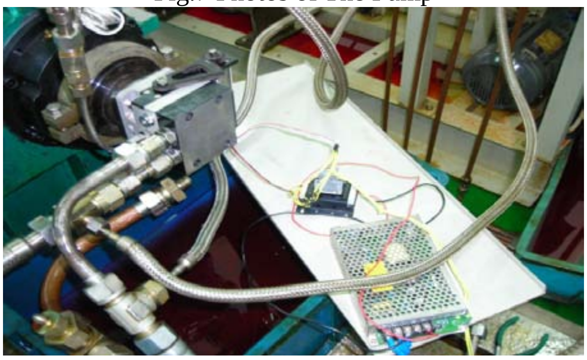


Fig.8. The Hydraulic System Test-Bed

4.1 Experiments of Swash Plate Swing Angle Regulating[6-8]

The step response curve of the servo system is shown in Figure 9. In which Red curve is the given signal, and the green curve is the response. The response of given sinusoidal signal is shown in Figure 10.

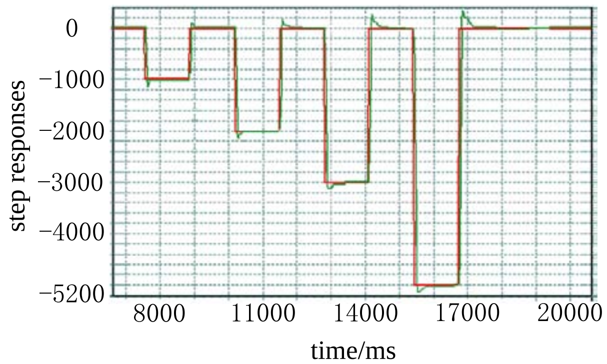


Fig.9 Step Responses of The Motor

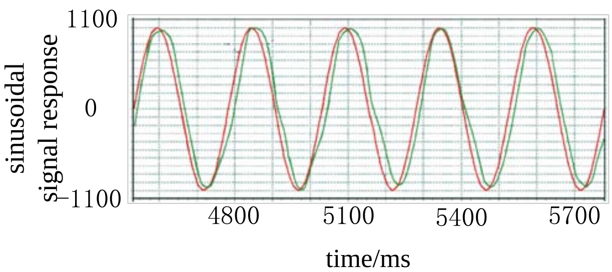


Fig.10. Sinusoidal Signal Response of The Motor

It can be seen that the response of different amplitude of the position step signals are basically the same. Take the response of -5000 (-1.3ml/r) for an example, the rise time is 120ms ,the overshoot is 2.3%, and the transition time of 5% error band is 310ms; When steps from -5000 (-1.3ml/r) to 5000 (1.3ml/r), the rise time is 100ms, the overshoot is 8%, and the transition time of 5% error band is 280ms. The system has fast response and high steady state accuracy. For a sinusoidal signal input, when the frequency is increased to 5.0Hz, the amplitude attenuation is 0.445dB and the phase-shift is 29.8° ,which shows that the bandwidth of the position servo system of the swash plate swing angle regulating motor is at least 5.0Hz. As the swash plate swing angle regulating motor comes with the controller, and communicates with the EHA-VPVM via serial ports, the higher frequency response cannot be tested due to the limitations of communication speed.

4.2 Experiment of The Whole Pump

The pump flow in conditions of different load pressures and speeds are shown in Figure 11 and Figure 12.

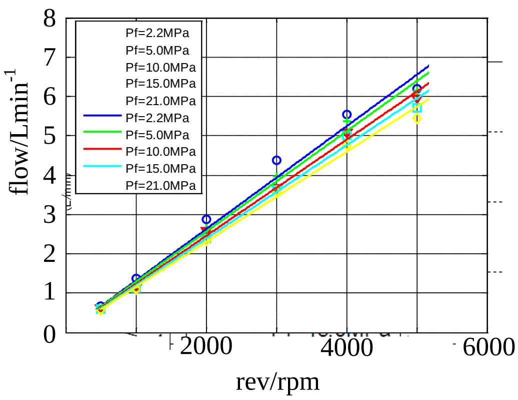


Fig.11. Flow-Rev Under Series of Pressures

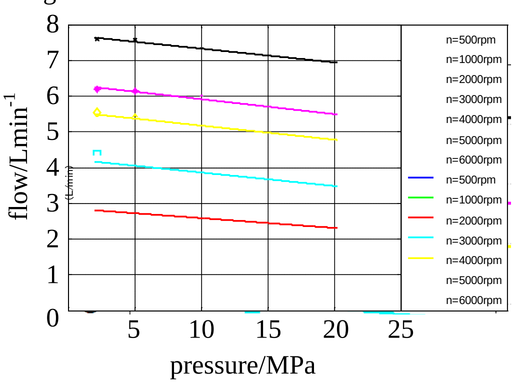


Fig.12. Flow-Pressure in Series of Revs

The volumetric efficiency of the pump is 95%. It can be seen from the figures that the reduction of the volumetric efficiency is little while the pressure increases, therefore the performance of the pump is relatively stable.

5 Conclusions

An electric servo variable pump, in which the swash plate is driven by a DC motor, is designed to meet the requirements of variable pumps in EHA. According to simulation analysis and experimental research, we found that the pump has the following advantages:

(1) The system is simplified by using a motor to actuate the swash plate directly instead of the hydraulic actuator and the oil sources;

(2) The link of servo valve that is vulnerable to pollution removed, make the reliability and antifouling of the pump be improved, and the control of EHA-VPVM system without servo valves be achieved;

(3) The swash plate is directly actuated by a motor, therefore the system is no longer dependent on the main motor which drives the pump. The output flow rate can be achieved bi-directional variable and consequently effectively, which improves the response characteristics of the system;

(4) A position servo control system is composed by combining the embedded control system, therefore the pressure, power and flow can be regulated without other additional hydraulic components;

(5) With the development of motor technology, the characteristics of fast dynamic response and high frequency response can meet the requirements of various hydraulic systems. In this paper, the developed system fully meets the requirements[7] through the motor that is used to drive the swash plate.

Theoretical and experimental results show that the variable electric servo pump can significantly improve the dynamic characteristics of the EHA, and provide a very useful basic component for the application and development of the EHA.

Acknowledgements

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