Design and Numerical Study of Electro-Hydrostatic Actuator

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Abstract. In order to improve the compactness and integration of electro-hydrostatic equipment to meet their miniaturization, a new electro-hydrostatic actuator (EHA) scheme is proposed, and the working principle and feature are introduced. The physical model of EHA is developed, numerical studies have been done to investigate the static and dynamic performances including the output force-pressure characteristics, the output speed-flow rate relationship, the load capacity and the dynamic response. The results show that: (1) the output force of the actuator is proportional to the working pressure and the output speed is proportional to the flow rate. (2) the EHA has a better load capacity, and the maximum output force is around 3720 N. (3) under a rated load of 3000N, the EHA has good dynamic performances with a rise time of 0.056s, an overshoot of 1.63% and a transient time of 0.17s. (4) the EHA can respond quickly and realize precise positioning. (5) the response time is related to the load, the pump displacement and the actuator effective area. The research results provide a theoretical basis for the development of high power density and efficient EHAs.

1. Introduction
In recent years, hydraulic equipment has faced the new development requirements such as miniaturization, high integration, and high power density etc.. Traditional hydraulic transmission systems are widely used in industry, agriculture, marine and aerospace fields by virtue of its advantages such as small size, high precision, wide speed range and diverse control methods. However, the inherent shortcomings of hydraulic systems restrict their development, such as leakage, pipeline shock, poor anti-pollution ability, low efficiency etc.. With the development of electronic control technology and the introduction of a new concept of Power-By-Wire, a new opportunity has emerged in the research and development of a new type of electro-hydrostatic equipment. So an integrated power transmission actuator named electro-hydrostatic actuator (EHA) appears in people's view, which integrates the advantages of traditional hydraulic system and electro-mechanical actuator. EHA is an actuator, which is driven by a separate motor and consists of integrated motor, hydraulic pump, hydraulic cylinder, hydraulic control components and accessories. It has the advantages of high power density, low noise, light weight, small size, safety and reliability etc.[1]

In the 1960s, EHA first appeared in the US Air Force's electric actuator program in view of a number of accidents on the US Air Force aircraft caused by the operating system[2]. The US Air Force, Navy, NASA and Moog jointly participated in the research of power transmission actuators, and
successfully completed the flight test of EHA on NASA F/A-18B SRA. The test shows that the actuation system has the same performance as the original device[3][4]. Woodward Company of the United States successfully designed and manufactured the 2nd generation power transmission actuator, and successfully applied to the latest batch of fighters by virtue of its compact structure, high degree of integration, excellent performance[5]. The KESP series products produced by Kawasaki include six specifications whose oil pump displacement is 22 ~ 140 m/min, motor power is 11 ~ 55 Kw and working pressure is up to 35 MPa[6]. In the development of EHA, Hamburg University of Technology, Germany first proposed the fuzzy control theory and realized the position control of the actuator[7].

However, China's research on EHA started late, and the previous research mainly focused on the theoretical research and technology development of EHA and now is officially invested in the development of products. Professors Wang Zhanlin and Fu Yongling of Beijing University of Aeronautics and Astronautics focused on system modeling, control methods, simulation and so on, and achieved a series of academic achievements[8][9]. Liu Yinshui of Huazhong University of Science and Technology invented a linear portable EHA with the advantages of compact structure, high integration, high power density, light weight and reliability, etc. It is expected to apply to the field of robots[10]. In recent years, Harbin Institute of Technology has made substantial breakthroughs in theoretical analysis and experimental research of EHA, and a variety of prototypes have been developed[11].

Based on the EHA schemes at home and abroad, this paper designs a new EHA scheme, elaborates its system composition and working principle, focuses on its structural characteristics. Based on AMESim simulation software, the EHA system is modelled and simulated, and finally the static and dynamic performances are analysed in combination with the simulation results.

2. System Composition and Working Principle of EHA

2.1. Structural Design

Referring to the previous research, a new EHA system was designed. Figure 1 shows the circuit diagram of EHA. The EHA system is a closed system. It mainly consists of single-bar double-acting hydraulic cylinder (HC), manual oil drain valve (MRVi), hydraulic control check valve (PCVi), safety valve (SVi, relief valve), filter (HF), servo motor (ESM), double-acting hydraulic pump (HGP), pressurized fuel tank (CPT), resistance ruler (RR), controller (EC), etc..

2.2. Working Principle

As shown in figure 1, the single-bar double-acting hydraulic cylinder and the fixed displacement pump form a closed circuit, and the controller transmits the control command to the servo motor to drive a fixed displacement pump, which can vary the pressure and flow by changing the speed and direction of the pump. When the servo motor rotates forward, the left side of the hydraulic cylinder is the oil supply circuit. When the pressure of oil supply circuit rise, the high pressure opens the hydraulic control check valve 2 and 4 to let the oil in the cylinder flows in the pump suction port, and the piston of hydraulic cylinder extends to the right. Conversely, when the motor rotates in the reverse direction, the right side of the hydraulic cylinder is the oil supply circuit, and the pressure rises. At the same time, the high pressure circuit opens the hydraulic control check valve 1 and 3 to complete the supply of the oil, and the actuator moves in the opposite direction. Thus, the direction of movement of the actuator is controlled by the motor steering.

In order to ensure the safety of the system, the system uses two safety valves to avoid excessive pressure on both ports of the hydraulic pump and the pressurized tank. In addition, two manual oil drain valves are used to realize oil release. On the one hand, it can avoid that the electronic control part cannot be operated normally due to malfunction or power failure, on the other hand, oil can be supplied in time to reduce the possibility of empty pump. The system uses a pressurized oil tank to prevent cavitation. Two hydraulic control check valves, which are connected to the hydraulic cylinder, can lock the piston position of the hydraulic cylinder in the case of a system shutdown[12].
3. Modelling and Simulation

3.1. Establishment of Servo Motor Simulation Model

The EHA system adopts direct drive volume control theory to control the speed of the servo motor through varying the voltage and frequency of alternating current[13]. This process includes two parts: the driver and the AC servo motor. The control signal is transmitted to the motor driver through the controller. The motor driver, which converts the alternating current with constant voltage and frequency into alternating current with variable voltage and frequency, drives the AC servo motor by outputting the sine wave and changing the voltage and frequency of the stator side of the motor. Therefore, the stepless speed regulation of the servo motor is realized.

Since the servo motor is a nonlinear multivariable object, the motor driver is regarded as a proportional link without regard to the dynamic response of the driver here. Then the relationship between the input control voltage of the motor driver $u_c$ and the output frequency of the motor driver $f_i$ is represented by:

$$f_i = K_u u_c$$  \hspace{1cm} (1)

The low voltage compensation of the motor can be ignored, the relationship between the phase voltage $U_i$ of the motor stator and the output frequency of the motor driver $f_i$ can be expressed as:

$$U_i = K_f f_i$$  \hspace{1cm} (2)

Irrespective of the electromagnetic transient generated in the motor operation and the voltage compensation, the electromagnetic torque of the asynchronous motor is described as:

$$T_e = \frac{3m_p}{2\pi R} K_f U_i - \frac{m_p^2}{40\pi R} K_i^2 n_p$$  \hspace{1cm} (3)

According to the torque balance condition, the motor torque balance equation is set up as:

$$T_e - T_i = J_d \frac{dn_p}{dt} + B_d n_p$$  \hspace{1cm} (4)

Considering the mechanical transmission loss of the motor, the load torque of the motor can be simplified as:

$$T_i = \frac{D_p p_p}{\eta_{pm}}$$  \hspace{1cm} (5)

where $f_i$ is the output frequency of the motor driver, $K_u$ is the gain factor of the motor driver, $u_c$ is the input control voltage of the motor drive, $U_i$ is the phase voltage of the motor stator, $K_f$ is the frequency voltage conversion factor, $T_e$ is the electromagnetic torque of the asynchronous motor, $m_p$ is the electromagnetic logarithm of motor, $R$ is the each phase resistance folded to the rotor of the stator side, $n_p$ is the actual motor speed, $J_d$ is the moment of inertia folded onto the motor shaft, $B_d$ is the friction damping of the motor, $D_p$ is the displacement of the pump, $p_p$ is the outlet pressure of the pump, $\eta_{pm}$ is the mechanical transmission efficiency of the motor.

3.2. Establishment of EHA System Model

Before modelling the EHA system, the following assumptions need to be made[14]:

- The bulk modulus of the oil is supposed to be a fixed value and there is no volume change caused by the incorporation of air into the oil.
- The effects of the pressure loss and the leakage of the pipeline can be ignored.
- It is supposed that the deformation of the joint between the hydraulic cylinder and the load is negligible and can be left out.
- The leakage of the hydraulic cylinder is assumed to have little effects on the system.

According to the circuit diagram of EHA, the simulation model is built in AMESim using mechanical library, hydraulic library, signal source and other modules, the simulation model of EHA as shown in figure 2. The position sensor is used to transmit the position signal of the hydraulic cylinder, and the computer compares the input specified position signal with the position signal fed back by the sensor to generate a deviation value, which is processed by the PID controller and output to the servo motor driver to drive the motor and the pump rotate. The strategy aims to push the actuator to move in the direction of reducing the deviation until the deviation is eliminated, and finally realizes the control of the displacement of the actuator. In addition, the manual unloading valve was replaced by the two-position and two-way electromagnetic directional valve to simplify the model.

Figure 1. The circuit diagram of EHA.

Figure 2. The simulation model of EHA.

3.3. Parameter Settings

After building the EHA system sketch under the sketch mode, enter the submodel mode, the EHA system uses the premier submodel function to create a complete system model. Enter the parameter mode, the system's parameter settings are shown in table 1.

Table 1. Parameter Settings Of Eha.

| Parameters of EHA              | Value | Units |
|--------------------------------|-------|-------|
| Piston diameter                | 25    | mm    |
| Piston rod diameter            | 18    | mm    |
| Piston displacement length     | 100   | mm    |
| Pump displacement              | 1.2   | ml/r  |
| Pump rated speed               | 3000  | r/min |
| Safety valve working pressure  | 16    | MPa   |
| Tank pressure                  | 1     | KPa   |
| Piston inertial mass           | 1     | Kg    |
| Cylinder static friction       | 30    | N     |

The EHA control strategy adopts a conventional PID controller, which is widely used in industrial systems due to its simple algorithm, mature control technology and superior utility. The conventional PID controller is a linear controller that divides the specified value from the actual output value to form a control deviation, and combines the proportional, integral, and differential steps of the
deviation into a control value to control the controlled object. The parameters of the PID controller are
determined by the trial and error method. In the simulation mode, the simulation results are repeatedly
tried and compared to determine the appropriate PID proportional coefficient, integral coefficient and
differential coefficient by using the function of batch parameters.

4. Simulation Analysis

After completing the parameter design for each component of the system, enter the simulation mode.
According to the simulation results, the static and dynamic performances of the system such as output
force-pressure characteristics, output speed-flow relationship, load capacity, and dynamic response are
analysed.

4.1. Static Performances

Through simulation test, the output force and differential pressure curve of the hydraulic cylinder are
obtained. Figure 3 shows the output force-pressure characteristics and the relationship between the
output speed and the flow rate of actuator are shown in figure 4. It can be seen that: (1) the output
force of the actuator is proportional to the working pressure and the output speed is proportional to the
flow rate. (2) the output force increases with the increase of the inlet pressure and the proportional
coefficient is equal to the effective working area of the piston. (3) the flow rate increases with the
increase of the output speed and the maximum speed tends to reach 0.4m/s.

![Figure 3. The output force-pressure characteristics.](image1)

![Figure 4. The output speed-flow rate relationship.](image2)

4.2. Dynamic Performances

Set a simulation time of 5s and a simulation step size of 0.01 for a simulation. Figure 5 shows the
pressure of relief valve under step signal. Input a constant load of 2000N from 0s to 1s, and add a load
of 4000N at the end of the 1st second. It can be seen that the relief valve reaches the cracking pressure
of 16MPa in approximately 1.5s under the sudden overload of 4000N and the system is protected by
unloading. Equally, the system has a better security.

Four different loads are given for a batch run under the simulation mode in order to verify the load
capacity of the system. Figure 6 shows the output force characteristics of actuator under different loads.
Several conclusions can be drawn: (1) the actuator can quickly meet the actuation requirements under
different load conditions, and the output force is stable. (2) under a load of 4000N, the load capacity of
the actuator is exceeded, and the maximum output force is around 3720N. (3) under a rated load of
3000N, the EHA has good dynamic performances with a rise time of 0.056s, an overshoot of 1.63%
and a transient time of 0.17s. The simulation curve shows that the system has better load capacity and
can achieve smooth output.

The command input of the cylinder position is set to be 0.09 m and the simulation time is set to be
1s to verify the performances of the EHA. Figure 7 shows the displacement of piston under different
loads. It can be concluded that: (1) the actuator responds quickly without overshoot. (2) the response
time increases with the growth of load, and does not exceed 0.1s. In fact, there is hysteresis in actuator

![Figure 7. The displacement of piston.](image3)
motion for the reason that it takes different time to build enough pressure and liquid with compressible volume to push different loads moving. The results also indicates that the system can control the displacement of the actuator by inputting the specified position command.

The dynamic performances of the EHA system can be compared and analysed from the response curve shown in the figure 8 and figure 9. Three different values of the pump displacement and the area of the piston rod are given respectively for a batch run under the simulation mode. From the simulation results in the figure 8, it can be seen that the system response speed becomes slow and the steady-state error increases with the decreasing of pump displacement. Because the displacement is proportional to the flow rate, and greater flow rate can lead to faster response. Similarly, figure 9 shows that the system error and response time increases with the increase of the area of the piston rod, which is due to the effect of the effective area of the actuator. Obviously, the effective area of the actuator decreases with the increase of the area of the piston rod. Therefore, the system dynamic characteristics will be better by increasing the pump displacement and reducing the effective working area of the actuator appropriately.

Figure 5. The pressure of relief valve under step signal.

Figure 6. The output force characteristics of actuator.

Figure 7. The displacement of piston under different loads.

Figure 8. Dynamic response with different pump displacement.
5. Conclusion
In this paper, a new type of electro-hydrostatic actuator is proposed. The structure and working principle are expounded. Simplified models of the EHA are established according to its structure and working principle. Theoretical and simulation analyses are conducted to investigate the dynamic and static performances of the system such as the output force-pressure characteristics, the output speed-flow relationship, the load capacity and the dynamic response. The simulation results verify the correctness of the EHA system. Several conclusions have been drawn as follows:

The output force of the actuator has a linear relationship with the pressure and the output speed is proportional to the flow rate both for theoretical and simulation results, the output force increases with the increase of the pressure and the flow rate increases with the increase of the output speed.

The simulation results confirm the superior control of the EHA system to the output force. The EHA can respond quickly and the response time increases with the growth of load. The system can control the displacement of the actuator by inputting the specified position command.

The pump displacement and the effective working area of the actuator exert great influence on the system dynamic characteristics. The increase of the pump displacement and the decrease of the effective working area of the actuator will be useful for developing high performance EHA.

The research results provide a theoretical basis for the development of high power density and efficient EHA.

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Figure 9. Dynamic response with different area of the piston rod.
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