Dynamic Analysis of Electro Hydrostatic Actuation System

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Abstract

More electric aircraft initiative has led to Fly-By-Wire (FBW) and Power-By-Wire (PBW) technologies. PBW technology has several advantages and has potential for weight reduction and energy saving compared to conventional hydraulic system. Recent development in aviation technology have combined the electric and hydraulic system and arrived at high performance Electro Hydrostatic Actuator (EHA) system. It is a one of the PBW technology which aims at replacing the centralized hydraulic system by a local self-contained and compact actuator system. It is an emerging technology which combines the benefits of conventional hydraulic system and direct drive actuators, like the high energy efficiency, high dynamic response, high torque to mass ratio and high maintainability. EHA system was initially introduced in aircraft for flight control system. Most of the current research literatures considered the EHA system with symmetric actuator configuration. This is because, most of the aircraft application uses symmetric cylinder. However in case of industrial application, asymmetric actuators are predominantly used. An indigenous experimental setup of EHA system with asymmetric actuator has been developed with sensors and instrumentation. In this paper, the dynamic analysis, position tracking and control of the EHA system by varying the speed of drive motor has been established using a Proportional Integral Derivative (PID) controller. PID tuning has been done using Ziegler Nichols (ZN) method. The response using of Proportional Integral (PI), Proportional Derivative (PD) and PID controllers has been studied and found that the PD controller gives the best response.

Keywords: Electro Hydrostatic Actuator; PD Controller; Asymmetric Actuator; Ziegler-Nichols method;

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1. Introduction

The earlier flight control system was operated by mechanical systems which are heavy and contribute to lot of fuel consumption. But recent advancement has led to fly-by-wire and power-by-wire technology. In spite of many advantages of FBW system, the disadvantage is that if a single actuator fails then the entire hydraulic system has to be stopped. Hence to avoid this consequence Power-By-Wire (PBW) technology came into existence. It completely replaces the centralized hydraulic system by a localized compact actuator system. The benefits of FBW are retained as it is and additional advantages are added by PBW technology to make the system more efficient and reliable. The need of PBW actuation system for the next generation all-electric aircraft concept has been explained [1]. Electro Hydrostatic Actuator (EHA) is a one of the power-by-wire technology used to actuate the flight control surfaces in aircraft. Electro hydrostatic actuator is a self-contained, modular and compact actuator system. It aims at replacing a centralized hydraulic system by a localized, self-contained and compact actuator system. Fig.1 shows the block diagram of EHA system. It mainly consists of controller, servo motor, pump, control elements and actuator (rotary/linear). The servo motor drives bi-directional pump in turn supplies oil to the actuator. The speed and direction of actuator is controlled based on speed and direction of servo motor. Hence the need of servo valve is eliminated. Actuator may be rotary or linear type depending upon the requirement. The controller gives output signal based on error between desired displacement and measured displacement. The development of a suitable controller is a prime importance in EHA system for better dynamic performance.

The three types of actuation systems- centralized hydraulic system, EHA and EMA have been described and the advantages in choosing EHA are elaborated [2]. EHA system was initially introduced in aircraft for flight control system and then gradually it is finding many applications in industries and robotics. There are basically three configurations of the EHA system available. They are EHA system with Fixed Pump and Variable Motor (FPVM), Variable Pump and Fixed Motor (VPFM) and Variable Pump and Variable Motor (VPVM). [3] Described an EHA configuration testing methodology to demonstrate the applicability of PBW technology on a primary flight control system. Work on control strategies for EHA has highlighted the relative merits of the different configurations [4]. The FPVM configuration of EHA is considered to have simpler structure and higher efficiency than EHA-VPFM. The EHA-VPFM has faster dynamic response than EHA-FPVM, but the efficiency is too low. In EHA-VPVM mode, the displacement and rotating speed of pump can be adjusted simultaneously, therefore, it can combine the advantages of the other two types of EHA. The performance of closed loop EHA with single rod cylinder load operation system has been analyzed [5].

The present paper deals with the development of the indigenous experimental set up of EHA system with FPVM configuration and asymmetric actuator. The schematic of the developed experimental test set up is shown in Fig.2. It consists of a DC motor which controls the speed and direction of the pump. The pump transfers the rotational motion of the motor to linear motion of the actuator. The position tracking and control of EHA is done by developing a control algorithm in Laboratory Virtual Instrument Engineering Workbench (LabVIEW) interfaced with experimental set up using Data Acquisition (DAQ) card. The detailed working and design of the EHA system is explained in section 2 and the controller developed to control and track the position of the actuator is being elaborated in section 3. Finally the performance of the EHA system with suitable controller is concluded in section 4.

Fig.1 Block Diagram of EHA
Fig. 2 Schematic Diagram of Developed Experimental Setup of Electro Hydrostatic Actuation System

**Nomenclature**

- $A_1$: Piston side area
- $D$: Volumetric displacement
- $e(t)$: Instantaneous error with respect to time
- $K_{cr}$: Critical proportional gain
- $K_p$: Proportional gain
- $P_{cr}$: Critical period of oscillation
- $P_m$: Servo motor power output
- $Q_p$: Flow delivered by pump
- $r(t)$: Desired value
- $T_d$: Derivative time constant
- $T_i$: Integral time constant
- $T_m$: Servomotor torque
- $u(t)$: Controller output
- $v$: Velocity of piston
- $y(t)$: Measured value
- $\omega_m$: Angular speed of motor
- $\omega_p$: Angular speed of pump
- $\eta_m$: Mechanical efficiency
- $\Delta P$: Differential pressure across pump
- $\eta_v$: Volumetric efficiency

**2. Design and Working of Electro Hydrostatic Actuator**

The Electro Hydrostatic Actuator system works on the principle of motor speed control unlike conventional system, which uses the servo valve for position control of actuator. The schematic of the developed experimental setup is shown in Fig. 2. The position set point is given in the Graphical User Interface (GUI) provided by LabVIEW software. The control signal is a motor speed signal which is given to servo drive of motor. The servo motor drives hydraulic pump and intern pump flow is delivered to cylinder. The cylinder is actuated to reach the desired position. The Linear Variable Differential Transformer (LVDT) measures the displacement of cylinder and gives position...
feedback to controller through DAQ card. The position feedback is given to controller to compare with set point. This forms the closed loop position control of cylinder. The servo motor speed and pressure level in hydraulic lines are continuously monitored. The controller subsystem contains computer with LabVIEW software and DAQ card. The Brushless DC (BLDC) servo motor and servo drive with power supply forms the electrical subsystem. The hydraulic subsystem contains Fixed Displacement Bidirectional Pump (FDBP), valve manifold that contains Pressure Relief Valve (PRV) and Non Return Valve (NRV), double acting asymmetric cylinder, hoses, pressure gauge and tank. The mechanical arm and loading arrangement with load forms the mechanical subsystem.

The static design calculation is the basis for sizing of each components of a system to achieve the required performance. The theoretical calculations are carried out to size the components and are selected based on the available standards in the market. There are two approaches to size the subsystems i.e., from prime mover to load side or vice versa. If the input power from the prime mover is fixed and the remaining subsystem sizes are determined based on the direction flow from the prime mover to the load side is called as top-down approach. On the other hand, if the load is fixed and the subsystem sizes are determined based on the direction flow from the load side to the prime mover is called the bottom-up approach. In the present work, top-down approach is considered for components sizing of EHA system. The BLDC servo motor [6] is the prime mover in EHA system. The power from the servomotor is represented as

\[ P_m = T_m \omega_m \]  

(1)

The power delivered by servo motor at maximum speed of 3000 rpm is 400W. The rated torque allowed on servo motor is 1.2 Nm. The servo motor torque is related to differential pressure across pump as given by

\[ T_m = \frac{\eta_m \Delta P D}{20\pi} \]  

(2)

The mechanical efficiency (constant) is assumed as 0.8. The differential pressure across pump is considered to be 21MPa. The flow generated by pump is given by

\[ Q_p = \eta_v \omega_p D \]  

(3)

The motor and pump are rigidly coupled and are assumed to be rotating at same speed. The pump flow is delivered to hydraulic cylinder. The pump flow and cylinder velocity in forward stroke is related as

\[ Q_p = A_1 v \]  

(4)

The calculations are carried out using equations from 1 to 4 and components sizes are chosen from the standard component sizes available in the market. The displacement of pump is selected as 1.48e-6m^3/rev. The cylinder piston side diameter is 0.02 m and rod side diameter is 0.012 m. The stroke length of cylinder is 0.05m.

The static design calculations are carried out to identify the size of components in subsystem. The calculated design parameters of all the components are given in Table 1. The indigenous experimental setup of EHA system is developed. The developed experimental setup as shown in Fig.3 is modular and compact with minimal piping. At most, care is taken to integrate the developed EHA system with sensors, instrumentation, data acquisition, and controller. The control algorithm employed and experimentations carried out further are explained in section 3.
Table 1 Design parameters of EHA

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power of motor</td>
<td>400 W</td>
<td>Max. pulse frequency</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Rated speed of motor</td>
<td>3000 rpm</td>
<td>Measuring range of LVDT</td>
<td>0 to 0.05m</td>
</tr>
<tr>
<td>Rated torque of motor</td>
<td>1.2 Nm</td>
<td>Accuracy of LVDT</td>
<td>±0.2%</td>
</tr>
<tr>
<td>Motor armature resistance</td>
<td>0.8 Ω</td>
<td>Volumetric disp. Of pump</td>
<td>1.48e-6 m³/rev</td>
</tr>
<tr>
<td>Motor armature inductance</td>
<td>1.3x10⁻³ H</td>
<td>Max. pump pressure</td>
<td>21 MPa</td>
</tr>
<tr>
<td>Motor inertia</td>
<td>3x10⁻⁵ kg-m²</td>
<td>Stroke length of Cylinder</td>
<td>0.05m</td>
</tr>
<tr>
<td>Motor shaft diameter</td>
<td>0.014m</td>
<td>Diameter of piston</td>
<td>0.02m</td>
</tr>
<tr>
<td>Incremental encoder</td>
<td>2500 PPR</td>
<td>Diameter of piston rod</td>
<td>0.012m</td>
</tr>
<tr>
<td>DC Supply Voltage</td>
<td>70 V</td>
<td>Max. operating pressure of PRV</td>
<td>34.5 MPa</td>
</tr>
<tr>
<td>DC Continuous current</td>
<td>8 A</td>
<td></td>
<td></td>
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</table>

3. Development of Control Algorithm

Electro hydrostatic actuator applications need a precise tracking and control of hydraulic cylinder. The purpose of EHA system is to achieve required position based on demand. The Proportional Integral Derivative (PID) controllers are widely used in industrial control application. This is because PID controller has simple structure and easy to implement in various systems. The challenge faced in PID controller is to tune the controller appropriately so that minimum rise time, minimum overshoot and minimum settling time are achieved. It works on the instantaneous error $e(t)$ between measured value $y(t)$ and desired value $r(t)$. The instantaneous error is given by

$$ e(t) = r(t) - y(t) \quad (5) $$

and the PID controller output is given by

$$ u(t) = K_p \left[ e(t) + \frac{1}{T_i} \int e(t) \, dt + T_d \frac{de(t)}{dt} \right] \quad (6) $$
The LabVIEW provides a platform to develop and implement the control algorithm. Controller is developed using PID virtual instrument module in the LabVIEW. The advantage of LabVIEW is that control algorithm can be changed at any point of time. In addition various control strategy can be developed and implemented without the need of change in hardware. Fig. 4 shows the PID controller program developed in LabVIEW software [7].

The PID controller acquires displacement sensor feedback and compares with the setpoint and generates frequency modulated square wave signal, which is given to servo drive of servo motor through DAQ card. LabVIEW provides GUI to change the controller gain (K_p), integral time (T_i) and derivative time (T_d). The PID controller needs to be tuned to get the required response.

3.1. PID controller tuning using Ziegler Nichols method

Ziegler-Nichols (ZN) tuning method is widely used method to tune the PID controller [8]. It gives tuning rules to determine the gain values (K_p, T_i and T_d). In this method integral gain and derivative gain are set to zero in Eq.6 and K_p is increased gradually until a sustained oscillation occurs for a step input signal. At point where sustained oscillation occurs, the critical proportional gain (K_{cr}) and the critical period of oscillation (P_{cr}) are obtained. From these values, the controller gains for PI, PD and PID are obtained using tuning rules given by ZN method. The tuning rules by ZN method is given in Table 2.

<table>
<thead>
<tr>
<th>Controller</th>
<th>Controller Gain (K_p)</th>
<th>Integral Time (T_i)</th>
<th>Derivative Time (T_d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>0.45 K_{cr}</td>
<td>0.83 P_{cr}</td>
<td>-</td>
</tr>
<tr>
<td>PD</td>
<td>0.45 K_{cr}</td>
<td>-</td>
<td>0.125 P_{cr}</td>
</tr>
<tr>
<td>PID</td>
<td>0.6 K_{cr}</td>
<td>0.5 P_{cr}</td>
<td>0.125 P_{cr}</td>
</tr>
</tbody>
</table>

Table 3 PID Controller Parameter Obtained by ZN Method

<table>
<thead>
<tr>
<th>Controller</th>
<th>Controller Gain (K_p)</th>
<th>Integral Time (T_i)</th>
<th>Derivative Time (T_d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PI</td>
<td>945</td>
<td>2.54</td>
<td>-</td>
</tr>
<tr>
<td>PD</td>
<td>945</td>
<td>-</td>
<td>0.38</td>
</tr>
<tr>
<td>PID</td>
<td>1260</td>
<td>1.52</td>
<td>0.38</td>
</tr>
</tbody>
</table>
The ZN method tuning is performed experimentally under no-load condition by increasing the $K_p$ to obtain sustained oscillation as shown in Fig. 5(a). The critical gain ($K_{cr}$) obtained from ZN method is 2100 and critical period of oscillation ($P_{cr}$) is 3.047 s. The controller gains for PI, PD and PID controller obtained from ZN method are tabulated in Table 3.

3.2. Response of PI, PD and PID controller

The experimental response of PI, PD and PID controller with gain values obtained from ZN method are shown in Fig. 5(b). The settling time of PI, PD and PID controller is 8s, 4s and 6s respectively. Hence PD controller has less settling time than PI and PID controller.

It is observed that the PI and PID controller have overshoot and PD controller has no overshoot. The piston is oscillating about the setpoint due to integral term is integrating error over time and giving output even after reaching the set point. But the controller output should be reduced to zero to reach to setpoint and this phenomenon is observed in PD controller. Hence, PD controller is selected for position tracking and control of hydraulic cylinder due to less settling time (4s) and no overshoot.

3.3. Position tracking and control of hydraulic cylinder in EHA system using PD controller

The PD controller is selected for the position tracking and control of hydraulic cylinder in EHA system because of less settling time and no overshoot. The PD controller has two parameters i.e., controller gain ($K_p$) and Derivative time ($T_d$). These two parameters are varied experimentally to observe the effect on response of the cylinder.

This subsection explains the effect of PD controller gain parameters on piston response. Fig. 6(a) shows the piston response with variation of control gain ($K_p$) for a target position of 0.025m with derivative time ($T_d$) is kept constant at 0.38s. The value of $T_s$ is kept constant at 0.38s as obtained from ZN tuning method. The value of $K_p$ is varied from 1000 to 1600 in steps of 200 for a step input signal of 0.025m. It is observed that, as $K_p$ increases, the rise time decreases and overshoot increases. This is due to the increase in controller output as described by Eq. (6).

The Fig. 6(b) shows piston response with variation of derivative time ($T_d$) for a target piston position of 0.025m with control gain ($K_p$) kept constant at 945 and is obtained by ZN method. The value of $T_d$ is varied from 0.00s to 0.36s in steps of 0.12s for a step input signal of 0.025m piston displacement. It is observed that, as $T_d$ is increased the system damping increases and overshoot reduces. The study of the effect of variation of gain parameters in PD controller on the piston response shows that the response of the system can be improved by scheduling the gain values.

Fig. 5 (a) Sustained Oscillations Obtained at Critical Gain ($K_{cr}$) of 2100, (b) Step Response for a Target Piston Position of 0.025m with Controller Parameters Tuned Using Zeigler-Nichols Method
4. Conclusion

Electro-hydrostatic actuator applications need a precise tracking and control of hydraulic cylinder. The purpose of EHA system is to achieve required position based on demand. The Proportional Integral Derivative (PID) controllers are widely used in industrial control application. This is because PID controller has simple structure and easy to implement in various systems. The challenge faced in PID controller is to tune the controller appropriately so that minimum rise time, minimum overshoot and minimum settling time are achieved. The contribution towards the development of EHA system includes:

- The indigenous experimental setup of EHA system is developed.
- The PID controller is used for position tracking and control of the actuator.
- The proportional, integral and derivative gains are obtained using Ziegler Nichols method. PI, PD and PID controller response is observed and found PD controller gives the best response.

During the study it has been observed that the PI and PID controller have overshoot and the piston is oscillating about the set point due to integral term is integrating error over time and giving output even after reaching the set point. But the controller output should be reduced to zero to reach to set point and this phenomenon is observed in PD controller. Hence, PD controller is selected for position tracking and control of hydraulic cylinder due to less settling time (4s) and no overshoot. The study can be further extended by implementing different control strategies to find the corresponding system behaviour and response.

References