Position Tracking Performance with Fine Tune Ziegler-Nichols PID Controller for Electro-Hydraulic Actuator in Aerospace Vehicle Model

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Abstract. Electro-Hydraulic Actuator (EHA) system is a third order non-linear system which is highly suffer from system uncertainties such as Coulomb friction, viscous friction and pump leakage coefficient which makes this system more complicated for the designing of the controller. The Proportional-Integral-Derivative (PID) controller has proposed in this paper to control EHA system and main problem in its application is to tune the parameter to its optimum value. Two different methods are used to tune the PID controller which are trial and error and Ziegler-Nichols method. MATLAB Simulink is used to simulate the system. In order to determine the performance of EHA system for the position tracking. 3 different of external disturbance such as 0N, 5000N and 10000N has been injected into the system. Simulation results show that the Ziegler-Nichols fine tuning method provides the better tracking performance when compared to the trial and error method for every specific disturbance setting. The Ziegler Nichols method provides better disturbance rejection as the performances indexes such as percentage overshoot, settling time and steady state error are not affected by the varying of disturbance.

1. Introduction

Electro-Hydraulic Actuator system consists of electro servo motor, bi-directional gear pump and actuator which is convert electrical energy to hydraulic power. When servo motor in EHA system rotates the gear pump, which, in turn, generate the flowrate. The pressure generated by the flowrate changes the position of piston rod [1]. The movement direction of the piston rod is related to rotational direction of the servo motor. Electro-Hydraulic system is being used in many various industrial field such as manufacturing system, active suspension system, mining machines fatigue testing, flight simulation, and etc [2].

Precision and fine control, high power to weight ratio, small size, good load matching, high environmental rigidity, quick dynamic performances, and a broad changeable speed range are all benefits of electro hydraulic servo systems [3].EHA offers strong positioning capabilities, which have a major influence on the above applications in terms of position control [4].Eventhough EHA system has advantages but this system is highly non-linear due to its system uncertainties which leads to degradation of the system in terms of its performance [5]. EHA system uncertainties that affect the system performance is servo valve pressure, control fluid volumes, stiffness and associated friction [6-7].

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Friction causes a number of issues into the system, including tracking errors, limit cycles, and poor stick-slip motion.

In order to surmount the drawbacks of the EHA system the proportional-integral-derivative (PID) controller has proposed in this study as a system controller for the Electro-Hydraulic controller system. The main problem occur when tuning the parameter for the controller due to its complexity and difficulties. There are many ways to tune the parameter but in this study Ziegler-Nichols is used to control the parameter of the EHA system. The performance of the system with the Ziegler-Nichols tuning method is discussed and presented below.

2. Methodology

2.1. Mathematics modelling of Electro-Hydraulic System

In order to model the EHA system, the mathematics equation is derived and obtained using each component of the system. A mathematical model of Electro-hydraulic actuator consists of the dynamics of the system disturbed by an external force. Figure below shows the physical model of the EHA system consists of a double acting cylinder with servo valve.

![Physical model of Electro-hydraulic actuator system](image)

**Figure 1.** Physical model of Electro-hydraulic actuator system

The actuator dynamic equation of EHA servo system is shown below

\[ m\ddot{x} = SPL - f\dot{x} - kxp - FL \]

The dynamic equation of EHA system with the external disturbance injected into its actuator is given as:

\[ \dot{x}_1 = x_2 \]
\[ x_2 = -\frac{k}{m} x_1 - \frac{f}{m} x_2 + \frac{S}{m} x_3 - \frac{F_L}{m} \]  
\[ \dot{x}_3 = -\frac{S}{k_c} x_2 - \frac{k_i}{k_c} x_3 + \frac{c}{k_c} \sqrt{\frac{p_a - x_3}{2}} k_v u \]

The EHA system equations is expressed in state space form as shown below

\[ \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{f}{m} & \frac{S}{m} & \frac{k_i}{k_c} \\ -\frac{k}{m} & -\frac{S}{k_c} & -\frac{k_i}{k_c} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{c}{k_c} \sqrt{\frac{p_a - x_3}{2}} \\ 0 \end{bmatrix} u \begin{bmatrix} 0 \\ \frac{F_L}{m} \end{bmatrix} \]

Table 1 illustrated the parameters of the EHA system which is describe in equation (5)

| Parameter                                               | Symbols | Value  | Unit       |
|---------------------------------------------------------|---------|--------|------------|
| Load at the EHA rod                                     | \( m \) | 0.33   | \( N s^2/cm \) |
| Piston area                                             | \( S \) | 10     | \( cm^2 \) |
| Coefficient of viscous friction                         | \( f \) | 27.5   | \( N s/cm \) |
| Coefficient of aerodynamic elastic force                 | \( k \) | 1000   | \( N/cm \) |
| Valve port width                                        | \( w \) | 0.05   | \( cm \) |
| Supply pressure                                         | \( p_a \) | 2100   | \( N/cm^2 \) |
| Coefficient of volumetric flow of the valve port        | \( c_d \) | 0.63   | -          |
| Coefficient of internal leakage between the cylinder chambers | \( k_l \) | 2.38 × 10^{-3} | \( cm^5/Ns \) |
| Coefficient of servo valve                               | \( k_v \) | 0.017  | \( cm/V \) |
| Coefficient involving bulk modulus and EHA volume       | \( k_c \) | 2.5 × 10^{-4} | \( cm^5/N \) |
| Oil density                                             | \( \rho \) | 8.87 × 10^{-7} | \( N s^2/cm^4 \) |

Equations (6), (7) and (8) are obtained after substituting the parameters into to the equation (2), (3) and (4) that represented below:

\[ A = \begin{bmatrix} 0 & 1 & 0 \\ -3030.30 & -83.33 & 30.3 \\ 0 & -40000 & -9.52 \end{bmatrix} \]  
\[ B = \begin{bmatrix} 0 & 0 & 3196 \\ 0 & \sqrt{2100 - x_3} \end{bmatrix}^T \]  
\[ C = [0 \quad -3.03 F_L \quad 0]^T \]
2.2. Modelling of system with MATLAB Simulink

The Electro-Hydraulic Actuator (EHA) system is modelled in MATLAB Simulink software. The mathematical equation of EHA system is used to design the system in MATLAB Simulink. Step input is given as the input for EHA system with initial condition is 1. In order to determine the performance of the EHA system, 3 types of disturbance, \( F_0 \) were injected into the system, which were 0N, 5000N, 10000N and PID controller is added in the Simulink model of the EHA system. Figure below shows the Simulink model of PID controller with Electro-Hydraulic Actuator system.

![Figure 2. EHA System Simulink model with PID controller](image)

2.3. Proportional-Integral-Derivatives (PID) controller design

A Proportional-Integral-Derivative controller is a control loop function which is widely used in industrial control systems and applications to regulate the parameter such as temperature, pressure, speed, flow ad etc. The controller output is summation of proportional, integral, and derivative outputs multiply with the error signal. The desired set point is SP and measured variable is PV from time to time variation. Both variables are derived from an error signal, \( e(t) \). The PID controller consists of 3 main coefficient, proportional gain (\( K_p \)), integral gain (\( K_i \)), and derivative gain (\( K_d \)). Figure 2.0 is illustrated the structure of PID controller. The controller output is summation of proportional, integral and derivative outputs multiply with the error signal.

![Figure 3. PID Controller](image)

The aim this controller is to reduce the error over time by changing the control variable, \( u(t) \). The formula of the PID controller can be written as below:

\[
u(t) = K_p e(t) + K_i \int_0^t e(t) \, dt + K_d \frac{d}{dt} e(t)
\]  

(9)
where,

\[ e(t) = SP - PV(t) \]

SP = set point,
PV = measured variable,
t is the time or instantaneous time (the present)

2.4. Ziegler-Nichols Tuning method

Ziegler-Nichols method is a heuristic tuning method which is a second classical method to tune the PID controller. Initially this method was developed by the J. G, Ziegler and N. B. Nichols in 1942. This tuning method is started with zeroing the integral gain and derivative gain and then raising the proportional gain until the system started to oscillate. The maximum value of proportional gain that make the system unstable is point of instability, \( K_u \) and period of oscillation is known as \( P_u \). The period of oscillation is the time the system takes to complete one oscillation. The value of proportional gain (\( K_P \)), integral gain (\( K_I \)), and derivative gain (\( K_D \)) can be determine using the formula from the table below.

| Controller | \( K_P \) | \( K_I \) | \( K_D \) |
|------------|-----------|-----------|-----------|
| PID        | \( 0.6 \times K_u \) | \( \frac{2K_P}{P_u} \) | \( K_P \times \frac{P_u}{8} \) |

3. Results and Discussion

In this section, the performance of the Electro-Hydraulic Actuator (EHA) system with the trial-and-error and Ziegler-Nichols tuning are presented in a table below with three types of disturbance input which are 0N, 5000N, and 10000N. Theoretically, the integral gain, (\( K_I \)) and derivative gain, (\( K_D \)) need to be shut down and increase the proportional gain, (\( K_P \)) until the system become unstable but practically the integral gain needs to be infinity and then tune the proportional gain to make the system oscillate. Tuning the integral gain to higher value make the gain to shut down. 0.8, 0.3, 0.4 are the maximum gains for 0N, 5000N, and 10000N respectively. The performance evaluation of each designed system is conducted with transient and steady-state analysis:

| Tuning Method | Trial-and-Error Tuning | ZN with Fine-Tuning |
|---------------|------------------------|---------------------|
| PID Gain      |                        |                     |
| \( K_P \)     | 0.30                   | 0.48000             |
| \( K_I \)     | 1.2                    | 0.59000             |
| \( K_D \)     | 0.01                   | 0.09672             |
The control parameter indexes of the PID controller for EHA system with 3 different values of external disturbances which are 0N, 5000N and 10000N are tabulated in Table 6. The performance output of trial and error and Ziegler Nichols method as shown in Figure 4, Figure 5, and Figure 6.

### Table 4. PID controller parameters for 5000N

| Tuning Method | Trial-and-Error Tuning | ZN with Fine-Tuning |
|---------------|------------------------|---------------------|
| PID Gain      |                        |                     |
| $K_p$         | 0.20                   | 0.18000             |
| $K_i$         | 0.90                   | 0.13660             |
| $K_d$         | 0.005                  | 0.05963             |

### Table 5. PID controller parameters for 10000N

| Tuning Method | Trial-and-Error Tuning | ZN with Fine-Tuning |
|---------------|------------------------|---------------------|
| PID Gain      |                        |                     |
| $K_p$         | 0.20                   | 0.2400              |
| $K_i$         | 1.00                   | 0.13750             |
| $K_d$         | 0.005                  | 0.10476             |

Figure 4. The response of the system with PID using Ziegler-Nichols tuning method and Trial-and-Error method for 0N
Figure 5. The response of the system with PID using Ziegler-Nichols tuning method and Trial-and-Error method for 5000N

Figure 6. The response of the system with PID using Ziegler-Nichols tuning method and Trial-and-Error method for 10000N

Table 6. Control performance indexes of each designed PID control system for 0N

| Method Control Performance Index | 0N           | 5000N        | 10000N       |
|---------------------------------|--------------|--------------|--------------|
| Tuning                          | Trial-and-Error Tuning | ZN with Fine-Tuning | Trial-and-Error Tuning | ZN with Fine-Tuning | Trial-and-Error Tuning | ZN with Fine-Tuning |
| Rise Time (s)                   | 3.57         | 5.22         | 4.13         | 11.70         | 3.91         | 12.00         |
| Settling Time (s)               | 165          | 120          | 192          | 121           | 193          | 164           |
| Percentage Overshoot (%)        | 78.5         | 52.1         | 76.7         | 56.0%         | 80.1         | 63.6          |
| Steady-State Error (m)          | 9.511x10^{-2} | 2.733x10^{-3} | 3.648x10^{-2} | 1.161x10^{-2} | 2.230x10^{-2} | 1.157x10^{-2} |
| Root Mean Square Error (m)      | 0.0975       | 0.0523       | 0.1910       | 0.1077        | 0.1493       | 0.1076        |
Ziegler Nichols method way better than trial and error method to tune the designed controller which produce more precise position tracking. Even though, the Trial and error method has produced satisfactory tracking performance in terms of rise time but Ziegler Nichols method provides better position tracking in terms of overshoot, settling time and steady state error. The Ziegler Nichols method for designed controller response faster to settling at steady state. This method has smaller percentage overshoot (51.1%, 56.0%, 63.6%) and faster settling time which hit the value at 120s, 121s and 164s compared to Trial and error method at three instants of disturbance respectively. Thus, the results show that Ziegler Nichols method has ability to produce more precise position tracking performance for PID controller as compared to the Trial and error method.

4. Conclusion
In this paper, two types of method to tune the PID controller has been used such as trial-and-error and Ziegler Nichols tune method. The PID controller is designed and the implemented into the EHA system that modelled using MATLAB Simulink software to evaluate the actual displacement of the actuator. Based on the results analysis, the Ziegler-Nichols with fine-tuned PID controller produce better performance as compared to the trial-and-error method in terms of settling time, percentage overshoot and steady-state error. Therefore, the proposed method which is Ziegler-Nichols with fine tuning method is best method in this project with highest weightage among other control performance indexes.

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References
[1] Han M K, Sung H P, J. H. Song, and Jong S K 2010 “Robust position control of electro-hydraulic actuator systems using the adaptive back-stepping control scheme,” Proc. Inst. Mech. Eng. Part I J. Syst. Control Eng., vol. 224, no. 6, pp. 737–746.
[2] S.M. Othman, Mohd F R, Sahazati M R, and Sazila S, 2015 “PID parameters optimization using PSO technique for nonlinear electro hydraulic actuator,” Jurnal Teknologi, vol. 77, no. 28, pp. 67–72.
[3] Sazila S, Mohd F R, and S.M.Othman, December 2015 “Electro-Hydraulic Actuator System Control via Pole Assignment Controller and Minimum Variance Controller,” Applied Mechanics and Materials, vol. 735, pp. 265–272.
[4] Mohammed M A A, Siti M O, Mohd F R, and Fahisal A, Oct 2019 “Optimization of pid for industrial electro-hydraulic actuator using PSOGSA,” Telkomnika (Telecommunication Comput. Electron. Control.), vol. 17, pp. 2625–2635.
[5] Claude K, Jean-Pierre K, and Maarouf S, Feb 2007 “Identification and real-time control of an electrohydraulic servo system based on nonlinear backstepping,” IEEE/ASME Trans. Mechatronics, vol. 12, pp. 12–22.
[6] Zulfatman H, Mohd F R, Abdul R H, Rozaimi G, and Sharatul I S, March 2012 “Perfect tracking control of an electro-hydraulic actuator with unknown disturbances,” Proc. - 2012 IEEE 8th Int. Colloq. Signal Process. Its Appl. CSPA 2012, pp. 341–346.
[7] S.M.Othman, Mohd F R, Sahazati M R, and Sazilla S, 2015 “Review on sliding mode control and its application in electrohydraulic actuator system,” Journal of Theoretical and Applied Information Technology, vol. 77, pp. 199–208.