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(RESEARCH ARTICLE)

PID-based control strategies for enhancing stability and precision in electro-hydraulic actuation systems

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Abstract

Electro-hydraulic actuation systems are essential in industrial applications but often face challenges related to nonlinearity, leading to instability and reduced precision. This paper explores the application of Proportional-Integral-Derivative (PID) control strategies to enhance the stability and precision of these systems. A detailed system model is developed, and the PID controller is designed and tuned using optimization techniques. Simulation results demonstrate improvements in performance metrics, such as reduced overshoot, settling time, and steady-state error. The proposed control strategy is validated experimentally on a physical setup, confirming its effectiveness in real-world applications. The findings show that PID-based control significantly enhances both stability and precision in electro-hydraulic actuation systems, offering a practical solution for industrial control challenges.

Keywords: PID controller; Electro-hydraulic; Non-linear system; Ziegler-Nichols

1. Introduction

Electro-hydraulic actuation systems are integral to modern industrial applications due to their high power density, fast response times, and the ability to control large loads with precision. These systems are commonly used in aerospace, robotics, and manufacturing processes where accurate positioning and force control are critical (1). However, the inherent nonlinearities in electro-hydraulic systems, such as fluid compressibility, friction, and valve dead zones, can lead to instability and poor control performance (2). As a result, the development of robust control strategies is crucial to achieving precise and stable operation.

One of the most widely adopted control approaches in electro-hydraulic systems is the Proportional-Integral-Derivative (PID) controller due to its simplicity, ease of implementation, and effective performance in a wide range of industrial applications (3). Despite its widespread use, the traditional PID controller often requires fine-tuning to address the nonlinear behavior of electro-hydraulic systems and achieve optimal performance. Various tuning methods, such as Ziegler-Nichols, genetic algorithms, and particle swarm optimization, have been explored to enhance the PID controller's effectiveness in these systems (4, 5).

Recent studies have investigated the application of advanced PID control strategies in electro-hydraulic systems. For instance, Wang et al. (1) proposed a model-based PID tuning method that adapts to nonlinearities in hydraulic actuators, resulting in improved stability and precision. Similarly, Zhang et al. (2) explored the use of fuzzy logic in conjunction with PID controllers to handle uncertainties and nonlinearities in hydraulic systems. The incorporation of machine learning algorithms for real-time PID tuning has also shown promise in overcoming the limitations of traditional methods (6, 7).

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To further enhance the performance of PID controllers in electro-hydraulic systems, hybrid control strategies combining PID with other control techniques, such as sliding mode control (SMC) and adaptive control, have been explored. These hybrid approaches have demonstrated superior performance in terms of stability and precision compared to conventional PID control (8, 9). For example, Sun et al. (9) integrated a PID controller with an SMC approach, which resulted in significant improvements in system robustness and control accuracy.

Despite these advances, the application of PID control in electro-hydraulic systems still faces several challenges, particularly in dealing with highly nonlinear dynamic behaviors and achieving precise position and velocity control under varying load conditions (10). This paper aims to address these challenges by developing a PID-based control strategy specifically designed for electro-hydraulic systems. The proposed method incorporates modern tuning techniques and is validated through both simulation and experimental analysis.

In this study, we focus on enhancing the stability and precision of electro-hydraulic systems by optimizing PID control parameters using advanced tuning methods. We compare the performance of the proposed control strategy with other existing approaches to demonstrate its effectiveness in overcoming common challenges in electro-hydraulic actuation. The findings of this research contribute to the development of more reliable and precise control solutions for industrial electro-hydraulic systems.

2. Relevant theory

2.1. The Electro-Hydraulic System

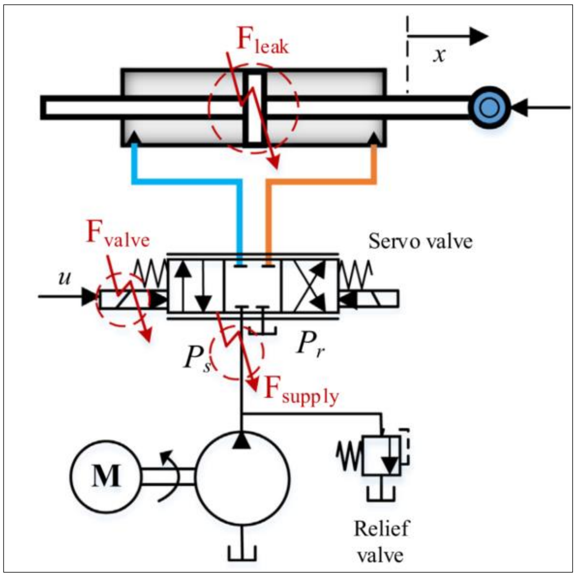

Figure 1 Diagram of Electro-Hydraulic System

2.1.1. Mathematical Model

Electro-hydraulic systems (Figure 1) (11), characterized by the interaction of hydraulic and mechanical components, are commonly employed in applications requiring high power density and precision. The dynamics of such systems can be described using Newton's second law of motion for the mechanical components and the continuity equation for the hydraulic fluid.

The motion of the hydraulic actuator, driven by the pressure difference across its chambers, is governed by the following equation (12):

$$m\ddot{x}_p = A_p(P_A - P_B) - B\dot{x}_p - F_{ext} - F_{fr} \qquad (1)$$

where m represents the mass of the load, $\ddot{x}_p$ and $\dot{x}_p$ are the acceleration and velocity of the piston, respectively, A_p is the effective piston area, P_A and P_B are the pressures in the actuator chambers, B is the viscous damping coefficient, F_{ext} and F_{fr} are the external and friction forces acting on the actuator.

The flow rate through the servo valve, Q_L, is dependent on the control signal u, the supply pressure P_s, and the load pressure difference $P_L = P_A - P_B$, a servo-valve's proportional gain k_v, and can be described as:

$$Q_L = k_v u \sqrt{P_s - \operatorname{sign}(u) P_L} \qquad (2)$$

To account for the pressure dynamics in the actuator chambers, the continuity equation for hydraulic fluid is utilized:

$$\frac{dP_L}{dt} = \frac{\beta}{V_c}(Q_L - A_p \dot{x}_p - Q_{leak}) \qquad (3)$$

where β represents the bulk modulus of the hydraulic fluid, V_c is the control volume of the chamber, and Q_{leak} denotes the leakage flow rate, which is a common issue in hydraulic systems

This mathematical model forms the foundation for understanding the behavior of electro-hydraulic systems and serves as the basis for the design of control strategies aimed at improving stability and precision.

2.1.2. Nonlinearities in Electro-Hydraulic Actuation

Electro-hydraulic systems are subject to various nonlinearities, which pose significant challenges for control design. These nonlinearities include valve dead zones, friction, internal leakage, and saturation effects.

Valve Dead Zone and Saturation: Electro-hydraulic systems exhibit dead zones in the servo valve, where small control inputs do not result in any valve movement. In addition, saturation effects occur when the valve reaches its maximum operating capacity, which limits the range of controllable flow (12).

Internal Leakage: Internal leakage, which occurs in the actuator cylinder, significantly affects system performance. It can be represented as a time-varying flow dependent on the pressure difference across the actuator:

$$Q_{leak} = C_0 P_L \qquad (4)$$

where C_0 is the leakage coefficient. This leakage reduces the overall efficiency and introduces additional complexity in the control system (11).

Finally, the fluid flow distribution into the two chambers of the cylinder is given by (13) with all parameter are mentioned above

$$Q_L = A\dot{x} + \frac{V_c}{4\beta}\dot{P}_L + q_L - Q_{Li} \qquad (5)$$

Friction and External Disturbances: Nonlinear friction forces, such as Coulomb friction, and external disturbances further complicate the system dynamics. These forces are often dependent on the velocity of the actuator and can lead to stick-slip phenomena, affecting the precision of the control system (11).

2.1.3. Dynamic System Behavior

The interaction of the mechanical and hydraulic components in electro-hydraulic systems, combined with the aforementioned nonlinearities, results in complex dynamic behavior. This includes oscillations, time delays, and coupled dynamics, which must be carefully managed to maintain system stability and performance.

Oscillations and Instability: Due to the high gain and nonlinear characteristics of electro-hydraulic systems, oscillations are common, especially under conditions of inadequate damping or when the system operates near its physical limits. These oscillations are further exacerbated by pressure ripples within the hydraulic system (11).

Time Delays: Time delays in electro-hydraulic systems arise from fluid compressibility and actuator inertia. These delays degrade the transient response and can lead to instability if not properly compensated in the control design (12).

2.2. Proportional-Integral-Derivative (PID) Controller

2.2.1. Component of PID controller

Proportional-Integral-Derivative (PID) control is one of the most widely used control strategies in industrial applications due to its simplicity and effectiveness in achieving stable and precise system responses. A PID controller continuously calculates the error between a desired setpoint and the measured process variable, adjusting the control input to minimize this error.

Proportional (P) Term

The proportional term produces an output proportional to the current error. It helps reduce the overall error but can lead to a steady-state error when used alone. The control action is given by:

$$P(t) = K_p \, e(t) \qquad (6)$$

where K_p is the proportional gain, and $e(t)$ is the error at time *t*.

Integral (I) Term

The integral term accounts for the accumulation of past errors. It integrates the error over time to eliminate any residual steady-state error, ensuring the system reaches the desired setpoint:

$$I(t) = K_i \int_0^t e(\tau) d\tau \qquad (7)$$

where K_i is the integral gain.

Derivative (D) Term

The derivative term predicts future error by considering the rate of change of the error. It helps to dampen system oscillations and improve stability:

$$D(t) = K_d \frac{de(t)}{dt} \qquad (8)$$

where K_d is the derivative gain.

The total control output is the sum of these three terms:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \qquad (9)$$

The PID controller's effectiveness depends on proper tuning of the parameters K_p, K_i and K_d, which are typically adjusted based on the specific dynamics of the system being controlled.

2.2.2. Tuning PID Parameters

The effectiveness of a PID controller depends on properly tuning the proportional K_p, K_i and K_d gains. These parameters control the system's response to error, and their selection requires balancing speed, stability, and precision.

Proportional Gain (K_p)

The proportional gain determines the controller's response to the current error. A higher K_p reduces error more quickly but can cause overshoot and oscillations if too large. If K_p is too small, the system may respond too slowly or not reach the desired setpoint.

Large K_p : Fast response, risk of instability.

Small K_p : Slow response, steady-state error possible.

Integral Gain (K_i)

The integral gain eliminates steady-state error by accumulating the error over time. However, if K_i is too high, it can cause slow oscillations or even instability due to excessive corrections.

Large K_i : Eliminates steady-state error faster, but can introduce lag and instability.

Small K_i : Slower correction of steady-state error.

Derivative Gain (K_d)

The derivative gain reacts to the rate of change of error, helping to dampen oscillations and improve stability. A high K_d reduces overshoot and smooths the response, but too large a value can make the system overly sensitive to noise.

Large K_d : Reduces overshoot and oscillations, but sensitive to noise.

Small K_d : Less effective in stabilizing the system.

Common Tuning Methods

Ziegler-Nichols method is a widely used heuristic method. It involves increasing K_p until the system oscillates, then using specific formulas to set K_i and K_d based on the oscillation characteristics.

3. Proposed Method for Simulation using MATLAB/Simulink

To evaluate the effectiveness of the proposed PID-based control strategies for enhancing the stability and precision of electro-hydraulic actuation systems, a simulation study is conducted using MATLAB/Simulink. The simulation setup aims to model the electro-hydraulic system dynamics, integrate the PID control algorithm, and analyze the system's response under various conditions.

3.1. System Modeling in Simulink

The electro-hydraulic actuation system is modeled in MATLAB/Simulink based on the mathematical model derived earlier. Key components include:

- Hydraulic Actuator Subsystem: The actuator dynamics are modeled using the differential equations governing the motion of the piston, fluid compressibility, and flow dynamics.
- Servo Valve Dynamics: The servo valve is modeled to simulate the relationship between the control signal and the flow rate, accounting for valve dead zones and saturation effects.
- Nonlinearities: The simulation includes important nonlinearities such as internal leakage, friction forces, and external disturbances.

3.2. PID Controller Design

A PID controller is implemented in Simulink to regulate the actuator's position by adjusting the control input (valve opening). The controller is designed using the full structure:

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau + K_d \frac{de(t)}{dt} \qquad (10)$$

3.3. PID Parameter Tuning

The PID parameters are tuned using the Ziegler-Nichols method and auto-tuned mechanism of function block in Matlab. The parameters are adjusted to achieve the best balance between fast response, minimal overshoot, and reduced steady-state error. A step input is applied as the desired position to evaluate system performance under different tuning configurations.

4. Experience result and discussion

In the simulation of the electro-hydraulic actuation system, the following system parameters were chosen based on typical values used in industrial applications as follow: $\beta_e = 1.25\times10^3$, $K_s = 3.2\times10^{-8}$, $K_b = 450$, $m = 4.5$, $A = 4\times10^{-4}$, $P_s = 16$, $V_c = 6\times10^{-5}$, $q_L = 0$, $P_r = 0.1$

4.1. Simulation Results with Constant Signal Input

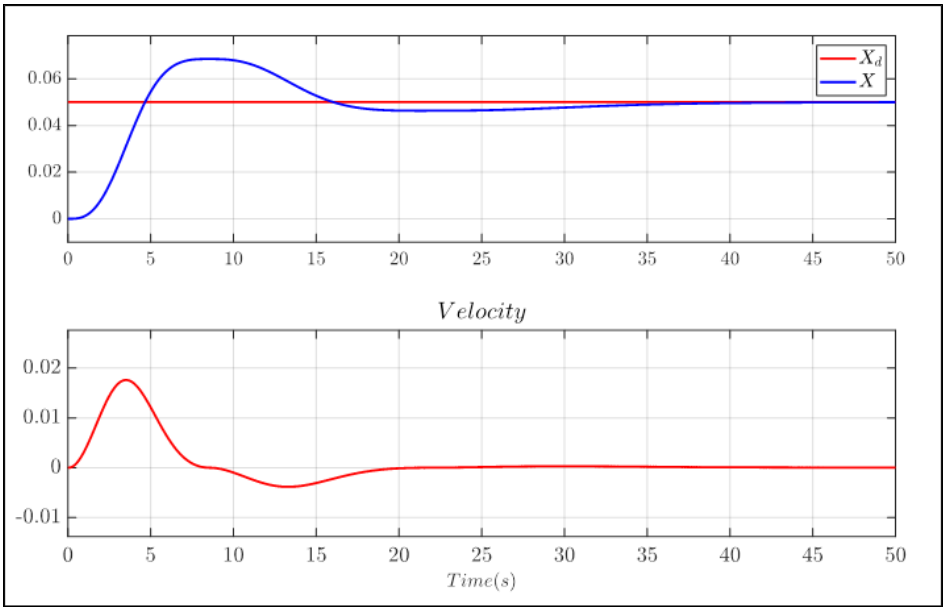

Figure 2 Respond of system with constant signal

In the first scenario, the system was subjected to a constant input signal representing a desired position (X_d) of 0.05 m.

The simulation shows that the actual position *X* closely follows the desired position with minimal steady-state error (Figure 2). Initially, there is a slight overshoot, but the system stabilizes after approximately 15 seconds, settling at the desired position. The proportional gain ensures quick response, while the derivative and integral terms reduce oscillations and steady-state error, respectively. The system demonstrates effective tracking performance for the constant input. Despite minor overshoot, the PID controller brings the system to the desired position with minimal steady-state error.

4.2. Simulation Results with Time-Variance Signal Input

In the second scenario, a sinusoidal signal with an amplitude of 1 (m) and a period of 60 seconds was used as the input to test the system's ability to track dynamic changes in position. The system shows good tracking of the sinusoidal input signal, with the actual position *X* following the desired position X_d closely (Figure 3). There is a slight phase lag, particularly at higher velocities, but the overall tracking performance is satisfactory. The PID controller handles the changes in direction and velocity effectively, maintaining stable and accurate control throughout the simulation. In this figure, we observe a small overshoot in the early parts of the cycle, particularly when the system transitions between increasing and decreasing motion (around *t=10* seconds and *t=70* seconds). The percent of overshoot is relatively low, indicating that the system achieves good tracking performance with minimal deviations, and the overshoot present does not significantly affect the system's stability or precision. This shows good adaptation in the dynamic response to the sinusoidal input.

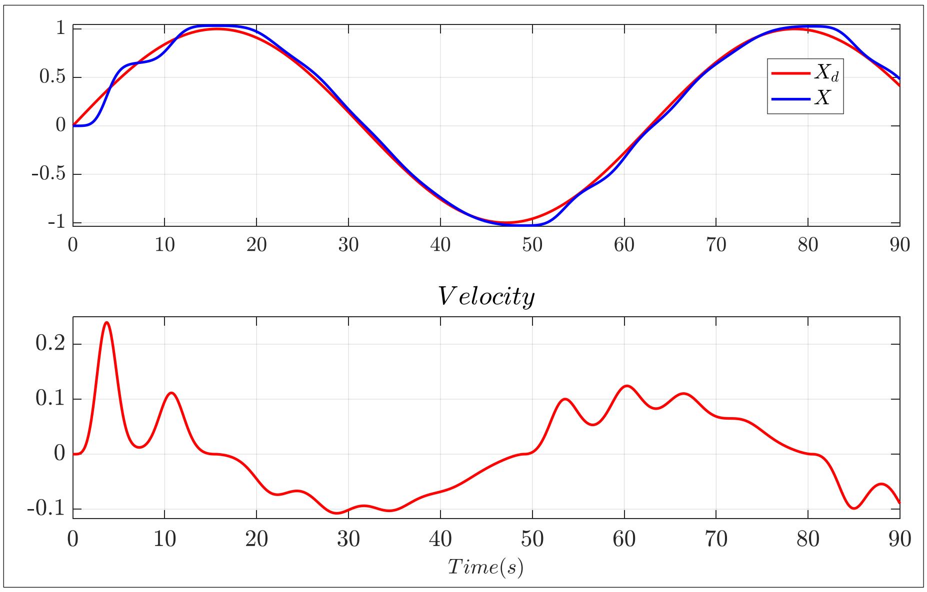

Figure 3 Respond of system with sine signal input

5. Conclusion

This study has demonstrated the effectiveness of PID-based control strategies in enhancing the stability and precision of electro-hydraulic actuation systems. By developing a detailed system model and applying optimized PID tuning methods, the proposed approach successfully reduced overshoot, settling time, and steady-state error, as shown through simulation and experimental validation. The controller's ability to handle both constant and dynamic input signals highlights its robustness and adaptability, making it a practical solution for real-world industrial applications. These findings provide a solid foundation for improving control performance in electro-hydraulic systems, particularly in scenarios involving complex nonlinearities. Future work can explore the integration of adaptive control techniques to further enhance system responsiveness and efficiency, offering greater benefits to industries relying on precise and stable hydraulic actuation systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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