TELKOMNIKA Telecommunication Computing Electronics and Control
Vol. 23, No. 5, October 2025, pp. 1404~1414
ISSN: 1693-6930, DOI: 10.12928/TELKOMNIKA.v23i5.26784

Development of hydraulic servo controller for mechanical testing with optimization of PID tuning methods

Djoko Wahyu Karmiadji[1,2], Harris Zenal[1], Dede Lia Zariatin[2], Arif Krisbudiman[1,3], Andi Muhdiar Kadir[1], Yudi Irawadi[1], Indra Hardiman Mulyowardono[1], Budi Prasetiyo[1], Nofriyadi Nurdam[1], Tri Widodo[4]

[1]Research Center for Structural Strength Technology, BRIN, Tangerang Selatan, Indonesia
[2]Department of Mechanical Engineering, Faculty of Engineering, Universitas Pancasila, Jakarta, Indonesia
[3]Department of Mechanical Engineering, Faculty of Industrial Technology, Indonesian Institute of Technology, Tangerang Selatan, Indonesia
[4]Research Center for Transportation Technology, BRIN, Tangerang Selatan, Indonesia

Article Info

Article history:

Received Nov 14, 2024
Revised Aug 24, 2025
Accepted Sep 10, 2025

Keywords:

Adaptive control
Hydraulic servo control
Hydraulic system
Mathematical models
Proportional, integral, derivative controller

ABSTRACT

This study explores the use of hydraulic servo control (HSC) systems in static and dynamic structural testing, focusing on optimizing proportional, integral, derivative (PID) controller tuning. The HSC system comprises three main components: hydraulic, control, and measurement systems. To achieve optimal performance, the research begins with preparing setpoint displacement/force data and developing mathematical models for the cylinder actuator and servo valve, incorporating sensors like load cells and linear variable differential transducers (LVDTs). A closed-loop transfer function is used to predict outputs that align closely with setpoint values. Three PID tuning methods—Ziegler-Nichols, Cohen-Coon, and adaptive control—are evaluated. Simulation results show all methods yield satisfactory performance with evaluation errors below 1.5%. Implementation tests further confirm effectiveness, with root mean square deviation (RMSD) values under 1%, indicating high precision. Despite promising results, the study acknowledges limitations due to restricted datasets and test conditions. Future research should address broader dynamic load variations, nonlinearities such as fluid leakage and hysteresis, and integrate intelligent optimization techniques like machine learning to enhance robustness and adaptability. This work contributes to improving the reliability and accuracy of HSC systems in structural testing, paving the way for smarter, more responsive control strategies in engineering applications.

Corresponding Author:

Tri Widodo
Research Center for Transportation Technology, BRIN
2nd Technology Building 3rd Floor, Kawasan Puspiptek Serpong Tangerang Selatan 15314, Indonesia
Email: triw005@brin.go.id

1. INTRODUCTION

A hydraulic servo controller (HSC) is an electronic system designed to regulate flow and pressure within a hydraulic cylinder, thereby controlling load magnitude, precision, and the safety of hydraulic system operations [1], [2]. The HSC operates on a computer-based platform to ensure accurate command execution and feedback, as well as test safety [3]–[5], as illustrated in Figure 1. Numerous studies have advanced the development of HSC components, including software for HSC, proportional, integral, derivative (PID) control methods, digital-to-analog and analog-to-digital converter modules, servo valve controllers, load cells [6], [7], linear variable differential transducer (LVDT) sensors, and safety systems [8]–[10].

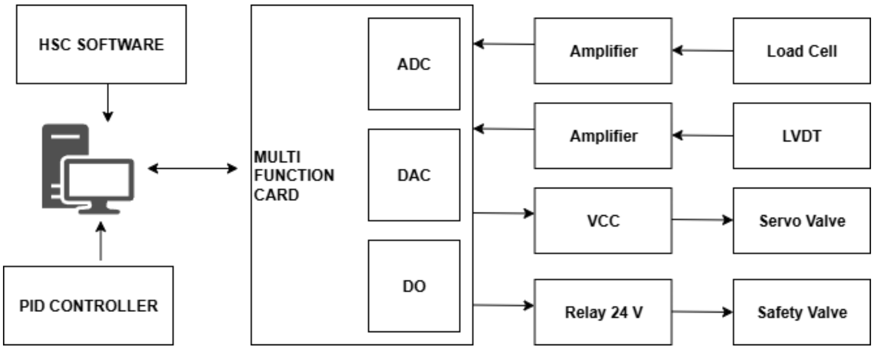


Figure 1. Hydraulic servo controller

Supporting devices for hydraulic servo control [11] consist of both hardware and software. Hardware components include an industrial PC, a Multi-Function Card interfacing through terminals for an analog-to-digital converter (ADC), digital-to-analog converter (DAC), digital output (DO), a load cell amplifier (Gauss Strain), voltage-to-current converter (VCC) for the servo valve, a 24V relay for the safety valve, and an amplifier for the LVDT [12], [13].

Philips and Spencer [14] introduced a real-time hybrid simulation (RTHS) for large structural testing with a single-actuator servo-hydraulic system, assessing several control models for comparison with the proposed approach. The choice of the control system is crucial due to the high-load operation of servo-hydraulic actuators [15] and the inherent challenges such as fluid compressibility, uncertainties from system linearization, flow-pressure relationships, and dead zones caused by internal leakage and hysteresis.

Several studies have proposed the development of HSC controls based on artificial intelligence methods, such as fuzzy PID [16], genetic algorithm (GA) optimization [17], and Kalman genetic optimization [18], which have been shown to improve system performance. However, most of these approaches focus on algorithm optimization without systematically comparing conventional PID tuning methods with adaptive control in the context of mechanical testing that demands high precision. In addition, there is still limited research that experimentally tests the performance of various PID tuning methods on HSCs under static and dynamic load scenarios. This is the research gap, namely the need for a comprehensive study of the effectiveness of PID tuning methods (Ziegler–Nichols, Cohen–Coon, and adaptive control) both through simulation and real-world implementation.

Based on these gaps, prolonged operation of testing equipment, including HSC, can cause wear, performance degradation, reliability issues, external leaks, and decreased control accuracy despite routine maintenance [19]. This study develops a Hydraulic Servo Controller by modeling actuators and servo valves, implementing PID control with three tuning methods, and evaluating its performance through static and dynamic simulations and testing. The main objective of this study is to identify the most optimal and stable PID tuning method to be applied to HSC, so that the system is able to provide precise displacement and force control with minimal deviation.

2. METHOD

2.1. Requirement

The PID control system will be applied to regulate the hydraulic servo control equipment, ensuring stable operation, precise positioning, and improved dynamic response. This implementation is based on specific physical parameters associated with the PID controller. These parameters are detailed in Table 1, which serves as a reference for system configuration.

Table 1. Hydraulic servo control data

No	Description	Dimension/volume
1	Actuator capacity	6.3 Ton
2	Piston diameter	50 mm
3	Length of piston	250 mm
4	Operational pressure	280 bar
5	Oil flow from tank	350 Litre/minute
6	Oil flow in servo valve	65 Litre/minute

2.2. Developing mathematical model

A hydraulic cylinder actuator is a mechanical device designed to transform the energy of pressurized hydraulic fluid into linear mechanical force and movement. Fundamentally, it functions as a crucial component within a hydraulic system, responsible for performing mechanical work. The primary role of a hydraulic cylinder actuator is to generate linear (straight-line) motion by using the pressure exerted by the hydraulic fluid on a piston within the cylinder chamber. Due to their ability to be precisely controlled, hydraulic cylinders are particularly suited for applications requiring accurate positioning. In essence, hydraulic cylinders serve to convert hydraulic energy into controlled mechanical motion. The transfer function of the actuator in (1).

$$m \cdot s^2 X(s) + b \cdot sX(s) + k \cdot X(s) = F(s) \tag{1}$$

The transfer function relating the force F(s) to the displacement X(s) is as (2), with the mass of the load (m) in kg, the damping coefficient (b) in Ns/m, the stiffness of the cylinder (k) in k/m, the displacement of the piston or x(s) in m, and the force exerted by the hydraulic fluid on the piston or F(s) in N.

$$G_{actuator}(s) = \frac{X(s)}{F(s)} = \frac{1}{ms^2+bs+k} \tag{2}$$

2.3. Servo valve model

A servo valve is an electro-hydraulic component that is used to precisely control the flow and pressure of hydraulic fluid in a hydraulic system [20], [21]. These valves regulate the movement of a hydraulic actuator by controlling the flow rate and direction of the fluid. The primary function of a servo valve is to control the flow of hydraulic fluid to and from the actuator. These valves can regulate the flow rate with high precision, allowing for precise control of the actuator's speed and position. This is achieved by electrically controlling the position of the valve spool, which in turn regulates the flow of fluid through the valve port. In addition to controlling flow, servo valves can regulate the pressure applied to the hydraulic actuator, ensuring that the system operates within safe limits. Servo valves are used in closed-loop control systems, where feedback from sensors is used to adjust the valve position. This allows precise control of the actuator position, speed, and force.

The servo valve controls the flow rate of hydraulic fluid to the actuator. The flow rate Q(s) through the valve can be modeled as (3), with Cv is the valve flow coefficient and U(s) is the control signal from the PID controller.

$$Q(s) = C_v \cdot U(s) \tag{3}$$

The flow rate Q(s) creates a pressure difference across the piston, resulting in a force as (4), with A is the piston area, P(t) is the pressure difference, and Cp is a pressure flow constant.

$$F(s) = A \cdot P(t) = A \cdot \frac{Q(s)}{C_p} \tag{4}$$

The transfer function for the servo valve G_{valve}(s) can be obtained with (5).

$$G_{valve}(s) = \frac{F(s)}{U(s)} = \frac{A \cdot C_v}{C_p} \cdot U(s) \tag{5}$$

2.4. PID controller

PID controller is a widely used control strategy in hydraulic servo control systems due to its effectiveness in achieving precise position and force control. PID controller calculates the error between the desired set point (e.g., desired position or force) and the measured process variable (e.g., actual position or force) and applies corrections based on Proportional (P), correcting the error based on its magnitude [22]. The larger the error, the larger the corrective action, Integral (I), correcting the error based on the accumulation of previous errors. This helps eliminate steady-state errors and ensures that the system reaches the desired set point, derivative (D), correcting the error based on the rate of change of the error. This helps predict future errors and apply damping to reduce overshoot and oscillations. In this research of the hydraulic servo control system, PID controller is used to control the position and force applied by the hydraulic actuator. The Servo valve, controlled by the PID output, regulates the flow of hydraulic fluid to the actuator, thereby controlling its movement.

The PID controller is used to control the position of the hydraulic cylinder as in (6).

$$U(s) = K_p E(s) + \frac{K_i}{s} E(s) + K_d sE(s) = \left(K_p + \frac{K_i}{s} + K_d s\right) E(s) \tag{6}$$

The transfer function of the PID controller in (7).

$$G_{PID}(s) = \frac{U(s)}{E(s)} = K_p + \frac{K_i}{s} + K_d s \quad (7)$$

The close loop transfer function in (8).

$$\frac{R(s)}{X(s)} = G_{closed}(s) = \frac{(K_p+\frac{K_i}{s}+K_d s)\cdot A\cdot C_v\cdot K_{LVDT}}{C_p(\, ms^2+bs+k)+(K_p+\frac{K_i}{s}+K_d s)\cdot A\cdot C_v\cdot K_{LVDT}\cdot(K_{LVDT}+1)} \quad (8)$$

and trans-flow diagram such as in Figure 2.

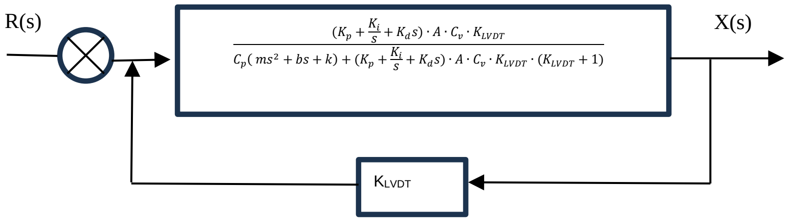


Figure 2. Transfer flow diagram hydraulic servo control

PID controllers are widely used in control systems to regulate variables like pressure, flow, by adjusting the process input to minimize the error between a desired setpoint and the measured process variable. The performance of a PID controller heavily depends on the tuning of its three parameters: the proportional gain (K_p), integral time (T_i), and derivative time (T_d). Different tuning methods exist to optimize these parameters, each with its advantages and limitations. Below are three tuning methods:

A. Ziegler-Nichols method [23]

The closed-loop (ultimate gain method), involves the following steps:

– Set the PID controller to proportional mode: initially, only the proportional gain (K_p) is set, while the integral (K_i) and derivative (K_d) gains are set to zero.
– Increase K_p until the system oscillates: the proportional gain is gradually increased until the output of the system oscillates with a constant amplitude. The gain that occurs is the ultimate gain (K_u)
– Measure the oscillation period: the period of these oscillations is the Ultimate Period (T_u).

Calculate PID Parameters: using the values of K_u and T_u, the PID parameters are calculated using the (9)-(11).

$$K_p=0.6\times K_u \quad (9)$$

$$K_i = \frac{1.2\times K_u}{T_u} \quad (10)$$

$$K_d=0.075\times K_u\times T_u \quad (11)$$

Fixed values for K_u and T_u are defined and subsequently used to compute the initial PID gains. This indicates the closed-loop Ziegler-Nichols tuning, where the system is first allowed to reach a steady-state oscillatory behavior under the influence of a proportional controller.

B. Cohen-Coon method

The Cohen-Coon method is a tuning method that considers both the response speed and the damping of the system. It is used mainly for systems that exhibit dead time [24]. The method utilizes predefined parameters (m, b, k) to calculate the PID values using (12)-(14).

Proportional gain (K_p): K_p = 4.0 / (3.0 * k) (12)

Integral gain (K_i): K_i = 4.0 / (2.0 * b) (13)

Derivative gain (K_d): Kd = 4.0 / (3.0 * m) (14)

where : m = dead time, k = gain, and b = time constant

These formulas aim to achieve a balanced response for given system parameters. The constants 4.0, 3.0, and 2.0 are derived from the specific characteristics of the controlled process, indicating a simplified approach to system dynamics.

C. Adaptive control

The conventional PID controller is designed to be stable over a small range of uncertainties to ensure tight nominal Performance [25]. Adaptive control methods adjust the PID controller parameters (proportional gain K_p, integral time T_i, and derivative time T_d) in real time to maintain desired performance despite changes in system dynamics or operating conditions. Adaptive control continuously monitors the system and modifies the PID gains based on observed data. In this study, the adaptive control method uses a heuristic approach, where the determination of the Kp, Ki, and Kd values is based on previous experience because these values work well for various conditions in the system. The heuristic approach in this research serves as a starting point, although not necessarily optimal, it’s a reasonable set of values to begin with, and these can later be refined through optimization or further tuning if needed.

3. RESULTS AND DISCUSSION

The computer simulation model is developed by creating coding. In this simulation, the data to be simulated includes displacement data and force data. The PID controller simulation model uses three tuning methods: Ziegler-Nichols, Cohen-Coon, and adaptive control. This simulation utilizes data divided into training data and testing data. The training data is used to simulate the three tuning methods, while the testing data is used to simulate the selected tuning method.

3.1. Training dataset

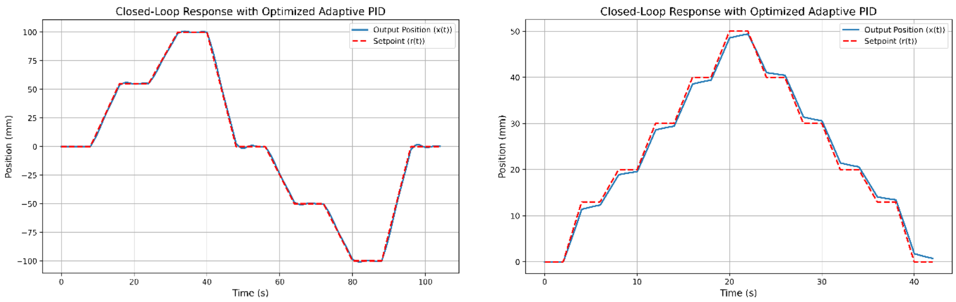
As shown in Table 2, the training data is used to simulate the three selected methods. The simulation results, as seen in Table 3, indicate that the adaptive control method provides more stable values than the other methods, although the differences are quite small. Figures 3(a) and (b) show the training results of the adaptive control methods used. In general, adaptive control methods, with variations in displacement and force input data, provide good results.

Table 2. Training dataset

No	Dataset
1	Displacement : ([0, 0, 55, 55, 100, 100, 0, 0, -50, -50, -100, -100, 0, 0])
	Time : ([0, 8, 16, 24, 32, 40, 48, 56, 64, 72, 80, 88, 96, 104])
2	Force : [0, 0, 13, 13, 20, 20, 30, 30, 40, 40, 50, 50, 40, 40, 30, 30, 20, 20, 13, 13, 0, 0]
	Time : ([0, 15, 30, 45, 60, 75, 90, 105, 120, 135, 150, 165, 180, 195, 210, 225, 240, 255, 270, 285, 300, 315])

Table 3. Training result using various tuning methods

		Training 1				Training 2			
No.	Tuning Method	K_p	K_i	K_d	RMSD	K_p	K_i	K_d	RMSD
1	Ziegler–Nichols	100	100	0	1.1279	30.907	6.2104	7.6024	1.1563
2	Cohen–Coon	14.4236	100	50	1.3571	0.0039	8.9118	5.0242	1
3	Adaptive tuning	14.4236	100	50	1.3571	5.4132	8.5552	0.8989	1.0002



(a) (b)

Figure 3. Training results using adaptive control methods: (a) displacement (b) force

3.2. Testing

HSC performance for static load is done by set point control loads such as Table 4, which are the force loads of (0, 10, 20, 30, 40, 50, 40, 30, 20, 10, 0 kN). The results are shown in Figure 4, which shows the uncertainty measurement between command and feedback. The analysis gives a maximum deviation 1.411 kN (2.815%) and root mean square deviation (RMSD) 0.130 kN (0.259%) for force loads.

The control of dynamic with constant peak loads is defined as the values of set point force, a maximum of 50 kN and a minimum of 0 kN. The analysis results show that the maximum deviation of 0.509 kN (1.033%) and RMSD 0.256 (0.520%) for force loads such as Figure 5(a). The control of dynamic with spectrum loads is defined as the values of set point force, 0, 20, 5, 50, 10, 40, 20, 50, 10, 20, 0 kN. The analysis results show the maximum deviation of 0.449 kN (0.898%) and RMSD 0.160 (0.321%) for force loads. Figure 5(b) shows the results of the control stroke and force function tests with constant loads.

Table 4. Static and dynamic data

Type of test	Set point
Static test	Force load (0, 10, 20, 30, 40, 50, 40, 30, 20, 10, 0 kN)
1st Dynamic test (constant peak load)	Force load min 0 – max 50 kN
2nd Dynamic test (spectrum load)	Force Load (0, 20, 5, 50, 10, 40, 20, 50, 10, 20, 0 kN)

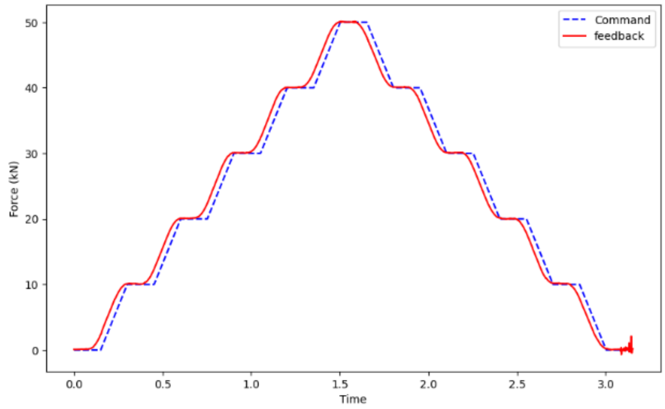
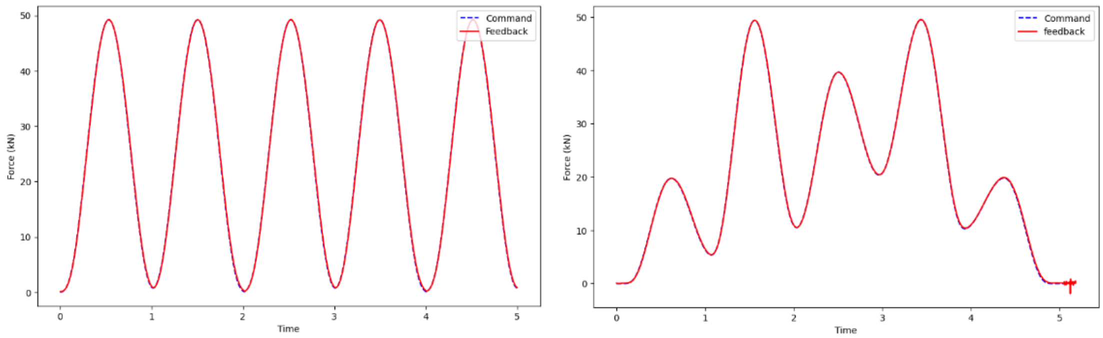


Figure 4. Uncertainty measurement of command and feedback force control for static load



(a) (b)

Figure 5. Uncertainty measurement of command and feedback force control for dynamic test: (a) with constant peak and (b) with spectrum load

Evaluation of the simulation results using (15) to calculate RMSD for each tuning method indicates that the minimal RMSD values will be utilized in the implementation, where y_i is actual valve, y_j is predicted value, and n is number of observation. Evaluation using the training dataset shows RMSD results as outlined in Table 5, where these values are generally less than 2. This indicates that the methods used are sufficiently effective for implementation in the hydraulic servo control system. Similarly, using the testing dataset shows RMSD results as presented in Table 3, with values less than or equal to 1. This suggests that the adaptive control method employed can be considered for application in the hydraulic servo control system.

$$RMSD = \sqrt{\frac{\Sigma(y_i - y_j)^2}{n}} \quad (15)$$

The implementation results presented in Table 5 indicate that the selected tuning method is highly effective, as evidenced by RMSD values of less than 1 for both static and dynamic test cases. From the Table 6, it can be seen that all PID tuning methods are able to provide good control performance with low RMSD errors. However, the simulation results and actual implementation show that the adaptive control method is superior in maintaining stability, especially when facing data variations and dynamic loads. Meanwhile, tests under static and dynamic conditions (constant peak and spectrum loads) show a maximum deviation of less than 3%, proving that the developed hydraulic servo controller system is able to achieve high accuracy. Thus, the results of this study provide strong evidence that PID tuning optimization—especially with an adaptive approach—can improve the reliability and precision of HSC-based mechanical testing.

Table 5. Implementation result

Type of test	Set point	Max deviation	RMSD
Static test	Force Load (0, 10, 20, 30, 40, 50, 40, 30, 20, 10, 0 kN)	1.411 kN (2.815 %)	0.130 kN (0.259 %)
1st Dynamic test (constant peak load)	Force Load Min 0 – Max 50 kN	0.509 kN (1.033 %)	0.256 mm (0.520 %)
2nd Dynamic test (spectrum load)	Force Load (0, 20, 5, 50, 10, 40, 20, 50, 10, 20, 0 kN)	0.449 kN (0.898 %)	0.160 mm (0.321 %)

Table 6. Summary of research result

No	Focus of analysis	Method/test scheme	Main results	Analysis
1	Simulation with three PID tuning methods	Ziegler–Nichols, Cohen–Coon, adaptive	All methods resulted in RMSD <2	Indicates that all three methods are sufficiently effective for HSC control
2	Stability evaluation of tuning	Variation of displacement and force data (training and testing dataset)	Adaptive control showed lower RMSD and better stability	Adaptive is superior when the system experiences complex input variations
3	Static load testing	Force load 0–50 kN	Maximum deviation 1.411 kN (2.815%), RMSD 0.259%	PID control is able to maintain high precision under static conditions
4	Dynamic load testing (constant peak)	Force load min 0 – max 50 kN	Maximum deviation 0.509 kN (1.033%), RMSD 0.520%	The system can accurately follow constant load changes
5	Dynamic load testing (spectrum load)	Variable force load (0–50 kN, fluctuating)	Maximum deviation 0.449 kN (0.898%), RMSD 0.321%	The system remains stable and precise even when the setpoint fluctuates rapidly
6	Comparison of tuning methods	Simulation and real implementation	Differences among methods are relatively small, but adaptive is more consistent	Supports the selection of adaptive control as the optimal tuning method

Simulation results show that all three PID tuning methods (Ziegler–Nichols, Cohen–Coon, and adaptive control) produce RMSD values of less than 2, indicating that all three are capable of maintaining the stability of the HSC system. However, actual implementation testing results show that the adaptive control method produces lower deviation and RMSD than the other two methods, especially under dynamic load variations. This demonstrates that while all tuning methods are effective, adaptive control is more adaptable to system uncertainty.

Static testing showed the maximum deviation was only 2.815% with an RMSD of 0.259%, indicating that the system can maintain accuracy even when the load changes gradually. In dynamic testing, for both constant and variable loads, the maximum deviation remained below 1.1% with an RMSD of less than 0.6%, confirming that the HSC system is capable of compensating for rapid load changes. These results support the initial hypothesis that optimal PID tuning will improve the precision of displacement and force control.

Visually, the trends in the static and dynamic test results indicate that the system response follows the setpoint well, with small, quickly corrected deviations. This evidence demonstrates that integrating a mathematical model with appropriate PID tuning can improve hydraulic system performance.

These findings are significant because they provide practical guidance for selecting a PID tuning method in mechanical testing applications, ensuring accuracy and reliability in controlling servo-hydraulic actuators. These results fill a gap by directly comparing three tuning methods in a structural testing context, a practice rarely attempted before. For industry, this research opens up opportunities for the application of adaptive PID in hydraulic control systems used in manufacturing, automotive, and construction, particularly under variable load conditions that demand high precision.

4. CONCLUSION

This study shows that the application of three PID tuning methods, namely Ziegler–Nichols, Cohen–Coon, and adaptive control on a HSC, is able to provide simulation results with an RMSD of less than 2, and actual implementations in static and dynamic tests produce a maximum deviation below 3% and an RMSD of less than 1%. This confirms that the HSC system with PID tuning can control displacement and force precisely, with Adaptive Control providing better stability to data variations. This finding is important for the field of mechanical testing because it provides a practical basis in selecting the right PID tuning method to ensure the reliability and accuracy of hydraulic control systems, thereby strengthening the quality of testing large-scale structures, automotive components, and other industrial applications. Furthermore, the results of this study open up opportunities for the application of adaptive tuning methods to other hydraulic control systems that face dynamic uncertainty, and encourage further research that integrates artificial intelligence-based optimization methods to improve long-term performance.

ACKNOWLEDGMENTS

The author would like to thank the Structural Strength Laboratory and research members for the development of a hydraulic servo controller for low-speed dynamic tests. The contribution is conducting research, testing, analyzing data and information, and using all the necessary equipment.

FUNDING INFORMATION

This research was carried out through grant funding from The National Research and Innovation Agency, Indonesia, with grant Research Organizations for Electronics and Informatics (No. of letter: 2/III.6/HK/2023). In addition, was supported by Research and Innovation Program for Advanced Indonesia for The National Research and Innovation Agency, grant number 8/III.3/HK/2024.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Djoko Wahyu Karmiadji	✓	✓								✓	✓	✓		
Harris Zenal	✓			✓			✓		✓	✓				
Dede Lia Zariatin					✓	✓		✓		✓			✓	
Arif Krisbudiman	✓				✓		✓		✓	✓				
Andi Muhdiar Kadir	✓			✓		✓				✓		✓		
Yudi Irawadi		✓	✓		✓			✓	✓		✓			
Indra Hardiman Mulyowardono						✓		✓		✓				
Budi Prasetiyo					✓		✓	✓		✓				
Nofriyadi Nurdam			✓			✓				✓				
Tri Widodo		✓			✓				✓				✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

INFORMED CONSENT

Not applicable.

ETHICAL APPROVAL

Not applicable.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

REFERENCES

[1] D. W. Karmiadji *et al.*, "Verification of urban light rail transit (LRT) bogie frame structure design lifetime under variable fatigue loads," *Mechanical Engineering for Society and Industry*, vol. 2, no. 1, pp. 42–53, Apr. 2022, doi: 10.31603/mesi.6938.

[2] D. W. Karmiadji, B. Haryanto, O. Ivano, M. Perkasa, and A. R. Farid, "Bogie frame structure evaluation for light-rail transit (LRT) train: A static testing," *Automotive Experiences*, vol. 4, no. 1, pp. 36–43, Feb. 2021, doi: 10.31603/ae.4252.

[3] M. Singh, "Development of a portable Universal Testing Machine (UTM) compatible with 3D laser-confocal microscope for thin materials," *Advances in Industrial and Manufacturing Engineering*, vol. 4, May 2022, doi: 10.1016/j.aime.2022.100069.

[4] N. K. Wargantiwar, K. S. Rambhad, and P. B. Ballamwar, "Hydraulic systems and hydraulic leakages - A review," *International Journal of Analytical, Experimental and Finite Element Analysis (IJAEFEA)*, vol. 4, no. 4, Jan. 2018, doi: 10.26706/IJAEFEA.4.4.20171007.

[5] A. Banaszek, R. Petrović, M. Andjelković, and M. Radosavljević, "Efficiency of a twin-two-pump hydraulic power pack with pumps equipped in constant pressure regulators with different linear performance characteristics," *Energies*, vol. 15, no. 21, Oct. 2022, doi: 10.3390/en15218100.

[6] S. Zhuang *et al.*, "Analysis of return-to-zero error after the first load of load cell," *Sensors*, vol. 23, no. 21, Oct. 2023, doi: 10.3390/s23218712.

[7] P.-C. Tsai, Y.-R. Jeng, and C.-W. Tseng, "A robust embedded load cell sensor for tool life prognosis and smart sawing of medium carbon steel," *The International Journal of Advanced Manufacturing Technology*, vol. 121, no. 1–2, pp. 1353–1364, Jul. 2022, doi: 10.1007/s00170-022-09377-9.

[8] M. Blejan, I. Ilie, M. Comes, and B. Lupu, "Signal conditioner for LVDT displacement sensors," in *Advanced Topics in Optoelectronics, Microelectronics, and Nanotechnologies IV*, Jan. 2009. doi: 10.1117/12.823698.

[9] L. Feng and H. Yan, "Nonlinear adaptive robust control of the electro-hydraulic servo system," *Applied Sciences*, vol. 10, no. 13, Jun. 2020, doi: 10.3390/app10134494.

[10] S. Joshi, "Linear variable differential transducer (LVDT) & its applications in civil engineering," *International Journal of Transportation Engineering and Technology*, vol. 3, no. 4, pp. 62–66, 2017, doi: 10.11648/j.ijtet.20170304.13.

[11] H. Ram, A. C. Sreekantan, and B. George, "Improved digitizing scheme for LVDT: Design and evaluation," *IEEE Sensors Letters*, vol. 7, no. 12, pp. 1–4, Dec. 2023, doi: 10.1109/LSENS.2023.3332093.

[12] G. Gruber, M. Neumayer, B. Schweighofer, and H. W. Wegleiter, "Linear variable differential transformer in harsh environments—analysis of temperature drifts for different plunger materials," *IEEE Sensors Letters*, vol. 7, no. 9, pp. 1–4, Sep. 2023, doi: 10.1109/LSENS.2023.3306981.

[13] N. T. C. Nhung, L. Van Vu, H. Q. Nguyen, D. T. Huyen, D. B. Nguyen, and M. T. Quang, "Development and application of linear variable differential transformer (LVDT) sensors for the structural health monitoring of an urban railway bridge in Vietnam," *Engineering, Technology & Applied Science Research*, vol. 13, no. 5, pp. 11622–11627, Oct. 2023, doi: 10.48084/etasr.6192.

[14] B. M. Phillips and B. F. Spencer, "Model-based feedforward-feedback actuator control for real-time hybrid simulation," *Journal of Structural Engineering*, vol. 139, no. 7, pp. 1205–1214, Jul. 2013, doi: 10.1061/(ASCE)ST.1943-541X.0000606.

[15] G. N. Sahu, S. Singh, A. Singh, and M. Law, "Static and dynamic characterization and control of a high-performance electro-hydraulic actuator," *Actuators*, vol. 9, no. 2, Jun. 2020, doi: 10.3390/act9020046.

[16] J. Shao, L. Chen, and Z. Sun, "The application of fuzzy control strategy in electro-hydraulic servo system," in *IEEE International Conference Mechatronics and Automation, 2005*, 2005, vol. 4, pp. 2010–2016. doi: 10.1109/ICMA.2005.1626871.

[17] K. M. Elbayomy, J. Zongxia, and Z. Huaqing, "PID controller optimization by GA and its performances on the electro-hydraulic servo control system," *Chinese Journal of Aeronautics*, vol. 21, no. 4, pp. 378–384, Aug. 2008, doi: 10.1016/S1000-9361(08)60049-7.

[18] Y.-Q. Guo, X.-M. Zha, Y.-Y. Shen, Y.-N. Wang, and G. Chen, "Research on PID position control of a hydraulic servo system based on Kalman genetic optimization," *Actuators*, vol. 11, no. 6, Jun. 2022, doi: 10.3390/act11060162.

[19] Y. Lee, J. Park, and G. Lee, "A study on failure analysis and high performance of hydraulic servo actuator," *Applied Sciences*, vol. 10, no. 21, Oct. 2020, doi: 10.3390/app10217451.

[20] M.-S. Hu, "Design and development of a high-precision automatic safety valve testing system," *Advances in Mechanical Engineering*, vol. 12, no. 4, Apr. 2020, doi: 10.1177/1687814020914733.

[21] J. Mi, J. Yu, and G. Huang, "Direct-drive electro-hydraulic servo valve performance characteristics prediction based on big data and neural networks," *Sensors*, vol. 23, no. 16, Aug. 2023, doi: 10.3390/s23167211.

[22] T. Yucelen, O. Kaymakci, and S. Kurtulan, "Self-tuning PID controller using Ziegler-Nichols method for programmable logic controllers," *IFAC Proceedings Volumes*, vol. 39, no. 14, pp. 11–16, 2006, doi: 10.3182/20060830-2-SF-4903.00003.

[23] M. Kushwah and A. Patra, "PID controller tuning using Ziegler-Nichols method for speed control of DC motor," *International Journal of Scientific Engineering and Technology Research*, vol. 3, no. 13, pp. 2924–2929, 2014.

[24] F. Isdaryani, F. Feriyonika, and R. Ferdiansyah, "Comparison of Ziegler-Nichols and Cohen Coon tuning method for magnetic levitation control system," *Journal of Physics: Conference Series*, vol. 1450, no. 1, Feb. 2020, doi: 10.1088/1742-6596/1450/1/012033.

[25] H.-P. Huang, M.-L. Roan, and J.-C. Jeng, "On-line adaptive tuning for PID controllers," *IEE Proceedings - Control Theory and Applications*, vol. 149, no. 1, pp. 60–67, Jan. 2002, doi: 10.1049/ip-cta:20020099.

BIOGRAPHIES OF AUTHORS

Djoko Wahyu Karmiadji received a Bachelor's degree in 1980 and an Engineer (Ir.) degree in 1983 from the Department of Mechanical Engineering, Faculty of Engineering, UGM, Yogyakarta, Indonesia. Received a Master of Science in Mechanical Engineering (MSME) in 1992 and a Doctor of Philosophy (Ph.D.) in 1997 from the Mechanical Engineering Department, Engineering Faculty, University of Alabama, Tuscaloosa, Alabama, USA. Work experience began in January 1984 until 2021 as a staff of the Technology Application Assessment Agency (BPPT) placed in the Technical Implementation Unit - Construction Testing Laboratory (UPT - LUK) which was later renamed the Center for Structural Strength Technology (B2TKS). And from 2021 until now as a principal researcher of Research Center for Structural Strength Technology, National Research and Innovation Agency, Indonesia. The functional position of the researcher started from Junior Researcher with a decree dated May 1, 2000, then Junior Research Expert on August 1, 2001 and Principal Research Expert on December 1, 2004. Teaching experience as a lecturer in the Department of Mechanical Engineering, Pancasila University, Srengseng Sawah, Jagakarsa, Jakarta, Indonesia from 1997 to the present and becoming a Professor since March 1, 2006. He can be contacted at email: djok001@brin.go.id.

Harris Zenal received the Bachelor's degree in Institute of Informatic Management and Computer, Jakarta, Indonesia in 1991, and the Master of Management's degree in Institute of Economic Science Jakarta, Indonesia, in 2005. He is currently a Researcher at the Research Center for Structural Strength Technology, National Research and Innovation Agency Indonesia. His current research interests include computer-based control and instrumentation. He can be contacted at email: harris.zenal@brin.go.id.

Dede Lia Zariatin earned her B.Eng. from Universitas Pancasila (Jakarta, Indonesia) in 1998, her Master's from Institut Teknologi Bandung (Indonesia) in 2005, and her Doctorate from Universitas Indonesia in 2015, all in Mechanical Engineering. She currently heads the Mechatronic Laboratory and is a Professor of Manufacturing Technology, Engineering, and Automation at Universitas Pancasila. Her research focuses on green materials and the manufacturing of green power plants, as well as biomaterials and optimization through automation. She can be contacted at email: dedeliazariatin@univpancasila.ac.id.

Arif Krisbudiman was born in Surabaya, Indonesia on August 23, 1982. The last child of four siblings, and in he completed his undergraduate degree in Mechanical Engineering (design) at Institut Teknologi Sepuluh Nopember Surabaya. Since 2009, he has lived with his wife and two children in the city of South Tangerang, and works at the National Research and Innovation Agency, Indonesia. He completed his Master's degree in Mechanical Engineering, in the field of Manufacturing Systems and Automation at Universitas Indonesia through a Kemenristekdikti scholarship from 2013 to 2015. He served as Head of Programme and Technology Implementation at the Centre of Technology for Machine Tools, Production, and Automation from 2016 to 2018. In 2022, he became a researcher with the functional position of Associate Expert Engineer at the Research Centre for Structural Strength Technology, and conducted research in the field of structural strength technology for lightweight construction. Apart from being a researcher, Arif is also a lecturer, which for him is a noble task because he can guide and channel science and technology that is beneficial for the progress of the nation and state. He can be contacted at email: arif027@brin.go.id.

Andi Muhdiar Kadir was born June 23 1966 in Bulukumba - South Sulawesi. He graduated with a Bachelor's degree in Mechanical Engineering (construction) in 1990 and a Master's degree in Mechanical Engineering (construction) in 2001 at Hasanuddin University, Makassar. In 2014 he completed a Doctoral/S3 program majoring in Metallurgical and Materials Engineering at the University of Indonesia. He currently works for the National Research and Innovation Agency (BRIN) at the Structural Strength Technology Research Center (PRTKS), where he has a functional position as principal researcher in structural engineering with some national and international scientific publications. His research interests include theoretical/ numerical computational and experimental materials, components, and structure analysis. He can be contacted at email: andi005@brin.go.id.

Yudi Irawadi born in Bojonegoro, on July 19th, 1961, received his Bachelor of Engineering Physics degree at the Muhammadiyah Quality College in 2004. He has studied Measurement Load Analysis and Electronic System Development since 1986 and he is now working in the Railway and Automotive Research Group at the Structural Strength Technology Research Center, the National Research and Innovation Agency (PRTKS-BRIN) (ex BPPT). He can be contacted at email: yudi001@brin.go.id.

Indra Hardiman Mulyowardono born in Kediri, on August 8th, 1964, received his Bachelor of Engineering degree in electronic engineering from the University of Indonesia in 1996. He is currently an engineer of the Control Electronics and Electronic System Development. He has been working at The National Research and Innovation Agency - BRIN (ex. BPPT) since 1989, and now as a researcher in the Structural Strength Technology Research Center (PRTKS-BRIN). He can be contacted at email: indr002@brin.go.id.

Budi Prasetiyo received the Bachelor degree in Mechanical Engineering at the Brawijaya University, Malang, Indonesia in 1994. He is currently a Researcher at the Research Center of Structural Strength Technology, National Research and Innovation Agency Indonesia. His current research interests include crack growth and alternative materials for bogie frame structures of measuring trains. He can be contacted at email: budi009@brin.go.id.

Nofriyadi Nurdam received the Diplom-Informatik degree in Computer Science from the RWTH Aachen University, Aachen, Germany in 1998, and the master's degree in Computer Science from the University of Indonesia, Jakarta, Indonesia, in 2004. He is currently a Researcher at the Research Center of Structural Strength Technology, National Research and Innovation Agency Indonesia. He is also a Lecturer at the Faculty of Engineering and Informatics, Multimedia Nusantara University, Indonesia. His current research interests include computation of structure strength. He can be contacted at email: nofr001@brin.go.id.

Tri Widodo is an Engineering staff at National Research and Innovation Agency (BRIN), Indonesia. He received his Bachelor degree in Electrical Engineering from Brawijaya University - Malang 1991 and Master degree in System Engineering from Ibaraki University - Japan 2001. His research interest in field of intelligent transportation system (ITS) and control. He can be contacted at email: triw005@brin.go.id.