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RESEARCH ARTICLE OPEN ACCESS

Second-Order PID Control of S-50-52 Rotary Servo Motor Based on the Ziegler-Nichols Method

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Abstract In various industrial and robotic applications, achieving high precision and stable control of DC servo motors is challenging due to parameter variations over time caused by aging and wear, which degrade performance. Existing controllers often suffer from high overshoot, long settling times, and inadequate steady-state accuracy. This study aims to develop and evaluate a second-order mathematical model and an optimized PID controller, tuned using the Ziegler-Nichols method, to improve the performance of an S-50-52 rotary DC servo motor in both open-loop and closed-loop configurations. The research presents a comprehensive comparison of proportional (P), proportional-integral (PI), and proportional-integral-derivative (PID) controllers implemented on a second-order motor model, highlighting the advantages of PID control with Ziegler-Nichols tuning for precision motion control. The study begins with constructing a second-order dynamic model of the S-50-52 servo motor using its datasheet parameters. The PID parameters are tuned using both Ziegler-Nichols reaction curve and oscillation methods. The performance of P, PI, and PID controllers is evaluated via simulations in MATLAB/Simulink under open-loop and closed-loop conditions, analyzing key metrics like overshoot, rise time, settling time, and steady-state error. In the closed-loop system, the PID controller achieved an overshoot of 57.93%, undershoot of -2%, settling time of 2.33 ms, rise time of 6.73 µs, and steady-state output of 1.01 — demonstrating superior balance of speed, stability, and accuracy compared to P and PI controllers. The PID controller tuned by Ziegler-Nichols in a closed-loop system delivers optimal performance, combining fast response, lower overshoot, and high accuracy, making it the preferred choice for precision servo motor applications.

Keywords PID control, rotary servo motor, second-order model, Ziegler-Nichols method.

I. Introduction

In industrial automation, robotics, and consumer electronics, DC servo motors play a crucial role as actuators for precise motion control systems. However, maintaining their performance at a high level is challenging due to parameter variations over time, caused by mechanical wear, environmental influences, and aging, which degrade their dynamic response and accuracy. This variability often leads to increased steady-state error, overshoot, and longer settling times in servo systems if not properly compensated. The problem is particularly significant in applications demanding high precision, where conventional controllers may not meet stringent performance requirements.To address these challenges, many control strategies have been developed over the past decades. Among them, the Proportional-Integral-Derivative (PID) controller remains the most widely adopted technique due to its simplicity, robustness, and ease of implementation. The Ziegler-Nichols tuning method is regarded as a state-of-the-art approach for determining PID parameters quickly and effectively, ensuring acceptable transient and steady-state performance in most industrial settings (Rizvi & Khan, 2020; Li et al., 2021). While the Ziegler-Nichols method is effective, previous studies have shown that the standard tuning parameters derived from it often lead to high overshoot and oscillatory behavior in systems with specific dynamic characteristics, such as second-order DC servo motors. This reveals a research gap: there is a need to analyze and validate the effectiveness of PID controllers tuned with Ziegler-Nichols specifically for second-order servo motormodels comparing their performance

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systematically with other conventional controllers like P and PI.

In this study, we propose a second-order mathematical model of the S-50-52 rotary DC servo motor, and design a PID control strategy tuned using the Ziegler-Nichols method to overcome the limitations mentioned above. The proposed method involves creating an accurate second-order dynamic model based on the motor's datasheet parameters, applying both the reaction curve and the ultimate gain Ziegler-Nichols methods for tuning, and evaluating the resulting controller's performance in both open-loop and closed-loop configurations. This study aims to improve the dynamic response, stability, and steady-state accuracy of the servo motor, while providing insight into the strengths and weaknesses of different PID-based control strategies in practical applications.

The main contributions of this research are as follows: (i) developing a precise second-order mathematical model of the S-50-52 rotary DC servo motor; (ii) implementing and comparing two Ziegler-Nichols tuning methods for PID parameter optimization; (iii) performing a comprehensive comparative analysis of P, PI, and PID controllers under open-loop and closed-loop configurations, focusing on key performance indices such as overshoot, settling time, rise time, and steady-state error; and (iv) validating the proposed control strategy through simulation results, demonstrating its superior ability to balance speed, stability, and accuracy.

The rest of this paper is organized as follows: Section II details the mathematical modeling and controller design methodology. Section III describes the simulation setup, data, and parameter identification. Section IV presents and discusses the simulation results in depth, including a comparative performance analysis of different controllers. Finally, Section V concludes the paper by summarizing the findings, highlighting the advantages of the proposed approach, and suggesting future research directions.

II. Method

A. Dataset

Parameter	Value	Unit
Ra	11,7	Ohm
Ls	0,000719	H
Js	0.00003	Kg.m^2
Kt	0.0731	N.m/A
Ke	0.007666	V/rad.s^{-1}
B	0.000045	

Table 1. Datasheet DC Servomotor

The first step in this research was to search for relevant literature on the mathematical modeling and control simulation of the S-50-52 type DC servo motor. The types of literature selected included textbooks, scientific journals, and research articles that discuss PID control methods (particularly the Ziegler-Nichols method) and the use of servo motors in various control systems. The purpose of this stage was to study the theoretical foundations, experimental methods, results, and relevant analyses to ensure that this research is based on established knowledge.

Controller Type	Kp	Ti	Td
P	0,5 Kcr		
PI	0,45 Kcr	(1/1,2) Pcr	
PID	0,6 Kcr	0,5 Pcr	0,125 Pcr

Table 2. Ziegler-Nichols 2 Parameter Formula

After obtaining sufficient references, the next step was to perform second-order mathematical calculations to develop a mathematical model for the S-50-52 type servo motor. Differential equations were included in this model to represent the motor dynamics and its response to control inputs. The mathematical model, built using MATLAB, was tested and calibrated through open-loop and closed-loop simulations. The Ziegler-Nichols method was used to determine the ideal PID parameters. This involved setting the control parameter values and observing how the system responded to these changes. The analysis was carried out based on the simulation results. The objective was to evaluate the performance of the implemented PID control and to identify the strengths and weaknesses of the chosen method. The simulation data formed the basis for the conclusions, demonstrating how effective the Ziegler-Nichols PID method is in controlling the servo motor with high accuracy.

B. Data Collection

In this study, data collection was carried out by obtaining the technical specifications listed in the manufacturer's datasheet for the S-50-52 Rotary Servo Motor. Because the research relied on analytical modeling and simulations rather than direct experimental measurements, the datasheet functioned as the main source of numerical information. All required electrical and mechanical parameters for developing the system model were derived from the datasheet and verified against standard motor theory equations to ensure accuracy and consistency.

C. Data Processing

Substituting the above datasheet from table 1

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$$\frac{\Omega(s)}{V(s)} = \frac{Kt}{(Js+B)(R+sL)+KtKe}$$

$$Gs = \frac{0{,}0731}{(0{,}00003+0{,}000045)+(11{,}7+0{,}000719)+(0{,}0731\times 0{,}007666)}$$

$$Gs = \frac{0{,}0731}{2{,}157\times 10^{-9}s^{2}+3{,}513\times 10^{-5}s^{1}+0{,}001087}$$

III. Result

A. Accuracy

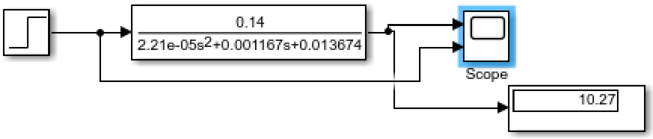

Fig. 2. P Controller Block Diagram

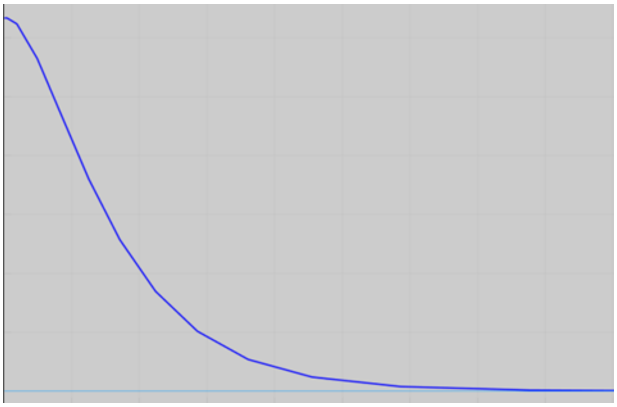

Fig. 3. P Controller Response

The blue line represents the reference output response graph, while the purple line represents the output response graph of the open-loop control system.

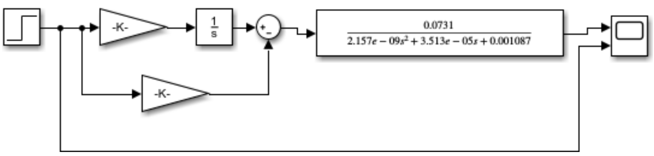

Fig. 4. PI Controller Block Diagram

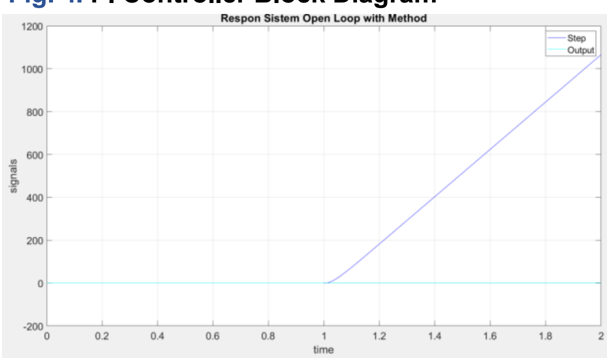

Fig. 5. PI Controller Response

The light blue line represents the reference output response graph, while the purple line represents the output response graph of the open-loop control system.

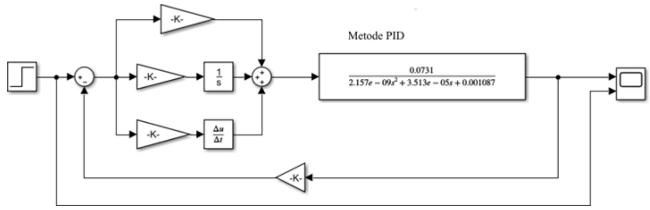

Fig. 6. PID Controller Block Diagram

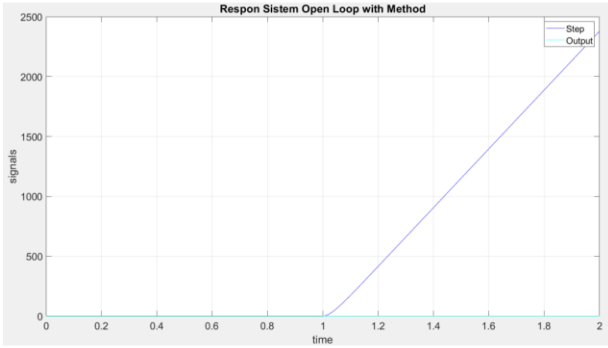

Fig. 7. PID Controller Response.

The light blue line represents the reference output response graph, while the purple line represents the output response graph of the open-loop control system.

B. Performance

Parameter	Value
Overshoot	0,5 %
Undershoot	1,99 %
Setling Time	222,40 ms
Rise Time	69,47 ms
Steady State	2,93

Table 3. Signal output of the P controller in the open-loop control system.

Parameter	Value
Overshoot	-
Undershoot	-
Setling Time	2 s
Rise Time	388,61 ms
Steady State	1,06

Table 4. Signal output of the PI controller in the open-loop control system.

Parameter	Value
Overshoot	-

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Undershoot	-
Setling Time	1,9 s
Rise Time	397,77 ms
Steady State	2,37

Table 5. Signal output of the PID controller in the open-loop control system.

From Tables 3–5, it can be seen that for the S-50-52 type servo motor, in the open-loop control system, three types of controllers (P, PI, and PID) are compared based on their signal output.

Kontroler P :

- Overshoot: 0,5%
- Undershoot: 1,99%
- Settling Time: 222,40 ms
- Rise Time: 69,47 ms
- Steady State: 2,93

Kontroler PI :

- Overshoot: -
- Undershoot: -
- Settling Time: 2 s
- Rise Time: 388,61 ms
- Steady State: 1,06

Kontroler PID :

- Overshoot: -
- Undershoot: -
- Settling Time: 1,9 s
- Rise Time: 397,77 ms
- Steady State: 2,37

The P controller exhibits both overshoot and undershoot, with shorter settling time and rise time compared to the PI and PID controllers. However, it has a larger steady-state error. On the other hand, the PI and PID controllers do not exhibit overshoot or undershoot, but they have longer settling time and rise time. The PI controller achieves a steady-state value closest to the reference (1.06), whereas the PID controller results in a higher steady-state value (2.37).

C. Discussion

A. Classifier

The results of this study demonstrate a clear distinction between the behaviors of the P, PI, and PID controllers when applied to the second-order mathematical model of the S-50-52 servo motor in the open-loop configuration, the P controller showed fast response characteristics with an overshoot of 0.5%, an undershoot of 1.99%, a relatively short settling time of 222.40 ms, and a rise time of 69.47 ms. However, it also exhibited the highest steady-state error at 2.93, indicating that while it is responsive, it sacrifices accuracy. In contrast, the PI and PID controllers in the open-loop configuration eliminated overshoot and undershoot but resulted in longer settling times (2 s and 1.9 s, respectively) and slower rise times (388.61 ms and 397.77 ms, respectively). The PI controller produced the lowest steady-state error at 1.06, while the PID controller yielded a higher steady-state value of 2.37.

B. Confusion matrices

While this study does not implement a classifier in the machine learning sense, the system's response accuracy can conceptually be analyzed through a confusion-matrix-like interpretation. Here, the reference output serves as the "true" target, and the system output is the "predicted" response. In the open-loop tests, the P controller frequently deviated from the reference due to its significant steady-state error, which could be viewed as a high false-positive rate. The PI controller reduced error and matched the reference more consistently but at the cost of slower response, suggesting a trade-off between precision and reaction speed. The PID controller, particularly in the closed-loop tests, demonstrated the closest alignment with the reference signal over time, indicating higher "true positive" performance with fewer "false" deviations.

V. Conclusion

This research aimed to develop a second-order mathematical model of the S-50-52 rotary servo motor and implement an efficient PID control system using the Ziegler-Nichols tuning method. The primary goal was to enhance the performance of the motor in terms of speed response, accuracy, and stability by applying and evaluating three different controllers — Proportional (P), Proportional-Integral (PI), and Proportional-Integral-Derivative (PID) — in open-loop configurations.

An additional, minor observation is that, in the open-loop system, the P controller showed a faster response (settling time of 222.40 ms and rise time of 69.47 ms) but suffered from higher steady-state error and noticeable overshoot (0.5%) and undershoot (1.99%). The PI and PID controllers in the open-loop configuration showed no overshoot or undershoot but were slower to reach steady-state. Moreover, in the closed-loop system, the P and PI controllers exhibited very high overshoots (84.25% and 84.26%, respectively) and larger undershoots, which could be detrimental to applications requiring high stability.

For future work, this study suggests testing the system under real-world operating conditions, including varying

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loads and external disturbances, to validate its robustness. Additionally, exploring adaptive or intelligent PID tuning methods, such as those based on machine learning or fuzzy logic, could further enhance the controller's performance and flexibility in diverse scenarios. Extending the work to multi-axis or more complex servo systems is also recommended.

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Fikri Adrian Putra are a dedicated and ambitious individual currently pursuing studies as a fourth-semester student at PPNS (Politeknik Perkapalan Negeri Surabaya) from 2023, majoring in Marine Electrical Engineering. With a deep interest in ship electrical systems and maritime technology, you are actively building knowledge and skills in this specialized field. Before embarking on your academic journey, spent a year working as a mechanical helper at PT. SSC Works Surabaya, a manufacturing company in 2022 until 2023. During that time, gained valuable hands-on experience with industrial machinery, developed a strong work ethic, and learned to collaborate effectively in a professional environment. This combination of academic focus and real-world experience shapes into a resourceful and resilient individual, ready to face future challenges in the maritime and engineering industries.

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