Optimization of Response Speed of DC Motor Based on PD Control

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Abstract. DC motors are widely used in various industrial control applications due to their efficiency, long life, and flexible speed regulation. However, their speed control systems often face issues like response delay, instability, and overshoot. Improving the precision, stability, and robustness of these systems is crucial. Traditional PD control models suffer from slow response speed and overshoot, necessitating improved control models.This work proposes a new PD control model optimized to enhance the response speed and stability of DC motor systems, aiming for fast response speed, no overshoot, and improved robustness.Initially, the PD controller parameters were tuned using MATLAB/Simulink simulations to identify ideal parameters (Kp = 20, Kd = 1.8). A new PD control model was then proposed to address the limitations of traditional PD models. A complete circuit was constructed and simulated using the Falstad simulation platform. Comparisons between the simulation results obtained in MATLAB/Simulink and Falstad verified the new model's effectiveness.The results showed that compared to traditional PD models, the new model offers fast response speed, no overshoot, and a simple structure. The new PD model effectively reduces overshoot while maintaining a response speed of 258.8 milliseconds, significantly improving stability and robustness.The proposed PD control model provides an efficient optimization scheme for designing speed control systems for DC motors. This study demonstrates that parameter tuning and circuit optimization can substantially improve performance. The new model offers enhanced precision, stability, and robustness, making it suitable for real-world DC motor control applications.

Keywords: PD controller, Output responses, DC motor

1 Introduction

Brushless DC motors have gained widespread usage in various industrial control applications due to their simple structure, high efficiency, wide speed regulation range, and long service life. They are frequently found in robotics, electric vehicles, and consumer electronics, making them essential components in modern industrial systems. However, achieving precise control of their speed remains a challenging task. Despite their many advantages, brushless DC motors often suffer from instability issues due to load variations and external disturbances. Furthermore, enhancing the precision, stability, and robustness of their speed control systems is crucial for improving overall system performance. This is one of the most urgent challenges facing engineers today [1, 2]. As industries demand quicker response times and reduced overshoot in motor speed control, existing control systems must evolve to meet these stringent requirements.

In the field of motor control, the Proportional-Derivative (PD) control system has proven to be a valuable approach due to its simplicity and effectiveness. It forms part of the Proportional-Integral-Derivative (PID) controller, differing only in its omission of the integral component. While the PD controller may lack the steady-state accuracy of a full PID controller, it offers certain advantages. Specifically, excluding the integral component eliminates the integral lag phenomenon often observed in high-inertia systems. This lag can result in slower system responses, leading to integral saturation issues and unexpected oscillations or response delays. Several researchers have highlighted the effectiveness of PD controllers in various applications, particularly where quick response and minimal overshoot are required. However, traditional PD controllers still exhibit limitations in precision and robustness [3, 4]. Recent studies have attempted to improve PD controller performance by incorporating fuzzy logic [5, 6], neural networks [7], and adaptive algorithms [8, 9], yet challenges in implementation and tuning remain.

Given these challenges, this paper aims to design a PD-based speed control system specifically optimized for brushless DC motors. The proposed system leverages both traditional and enhanced PD controllers to achieve rapid response speeds with minimal overshoot. By establishing a simulation model using Falstad and MATLAB/Simulink, the PD control system's performance was evaluated under various conditions. The simulation results demonstrate that the PD controller offers quick

Y. Yue (ed.), *Proceedings of the 2024 International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2024)*, Advances in Engineering Research 240,
https://doi.org/10.2991/978-94-6463-518-8_56

under various conditions. The simulation results demonstrate that the PD controller offers quick response and stable speed regulation, effectively reducing overshoot and improving system robustness. The paper is organized as follows: In the first section, we review the fundamentals of PD control theory. The second section details the simulation setup and parameter tuning strategies employed. In the third section, we analyze the simulation results obtained in Falstad and Simulink, comparing traditional and enhanced PD control models. Finally, the conclusion summarizes our findings and offers recommendations for future work in this field.

2 PD Control Theory

The Proportional Derivative (PD) is a type of feedback controller whose output [3], a Control Variable (CV), is generally based on the error (e) between some user-defined Reference Point (RP) and some measured Process Variable (PV) [4]. Based on the error each element of the PD controller performs a particular action.

Proportional (Kp): Hence, error is multiplied by a gain Kp, an adjustable amplifier. In many systems, Kp is responsible for process stability: too low, and the PV will drift away; too high, the PV will oscillate.

Derivative (Kd): The rate of change of error multiplied by a gain, Kd. In many systems, Kd is responsible for system response: too high and the PV will oscillate; too low and the PV will respond sluggishly. The designer should also note that derivative action can amplify any noise in the error signal. Tuning of a PD controller involves the adjustment of Kp, and Kd to achieve some user defined "optimal" character of system response [5]. The basic structure of the feedback control system is shown below(see Fig. 1):

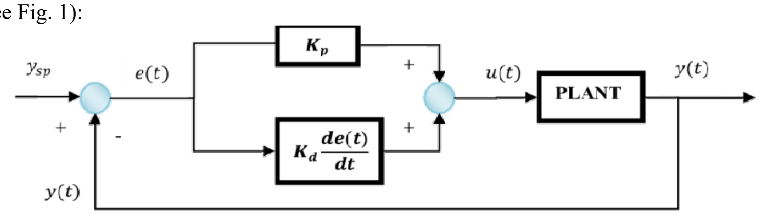

Fig. 1 PD control diagram (Photo credited: Original)

Formula is as below:

$$u(t) = K_p * e(t) + K_d * \left(d\frac{e(t)}{t}\right) \quad (1)$$

3 Simulation and Parameter Adjustment of Simulation System

3.1 Simulation Design

This work first used MATLAB/Simulinkfor simulation, which helped analyze the circuit's operation visually in advance [6-8]. In Simulink, this work simply set up a DC motor with the transfer function 3/(0.1*s^2+s) and configured the PD controller with Kp=1 and Kd=1 (see Figure X). During the tuning process of the motor's PD parameters, several empirical guidelines can be followed. Generally, it's advisable to adjust the proportional gain Kp first, and then tune the derivative gain Kd. Each parameter should be tested incrementally, starting from smaller values and gradually increasing to find the optimal settings.

For a virtual experimental platform, beginners are encouraged to experiment more boldly with parameter tuning to deepen their understanding of each coefficient's contribution to the system. Adjusting the gains in different proportions provides valuable insights into their individual and combined effects on system stability, response speed, and overshoot. Fig. 2 and Fig. 3 showed the system flow chart and PD controller settings, respectively.

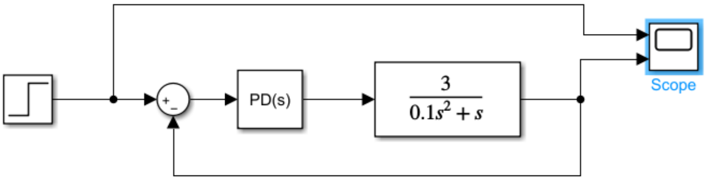

Fig. 2 System flow chart (Photo credited: Original)

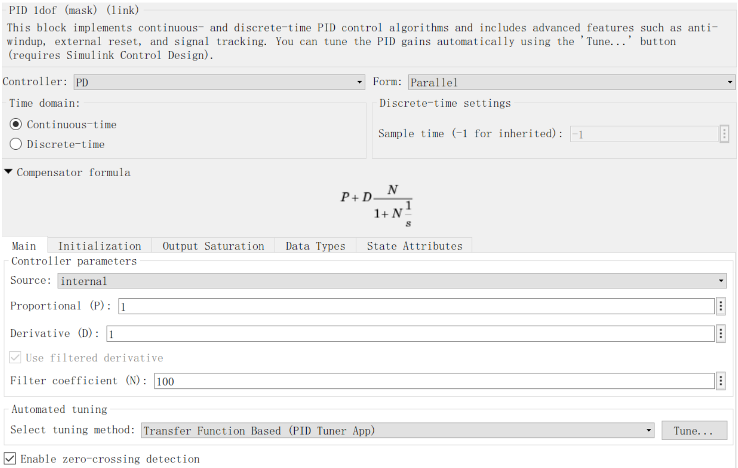

Fig. 3 PD controller settings (Photo credited: Original)

3.2 Detailed Analysis

In the figures above, the yellow line represents a square wave signal, and the blue line is the response curve.

Fig. 4(a): In this case, with Kp=1 and Kd=1, the system demonstrates a slow response speed. The motor takes around 6 seconds to reach steady state, coinciding with the square wave signal, but there is no steady-state error. This slow response indicates that the proportional gain is too low to provide the necessary speed.

Fig. 4(b): In case 2,increasing Kp to 10 while keeping Kd at 1 significantly improves the response speed, reducing the time to reach steady state to approximately 1.5 seconds. This indicates that increasing the proportional gain enhances the system's responsiveness.

Fig. 4(c): for this case,with Kp=20 and Kd=1, the response speed is further improved. However, the higher Kp results in a noticeable overshoot, demonstrating that while increasing the proportional gain improves response speed, it also leads to instability.

Fig. 4(d): in case 4,increasing Kd to 1.8 while keeping Kp 20 reduces the overshoot and increases the recovery speed, ensuring that the motor reaches the desired speed quickly without significant oscillations. The steady-state error remains zero, and the system achieves the fastest response speed while maintaining stability.

After extensive tuning of Kp and Kd, it was determined that the combination of Kp=20 and Kd=1.8 provides the optimal balance between response speed and stability. The system achieves the fastest response speed while minimizing overshoot, resulting in a highly satisfactory control solution for DC motor speed regulation.

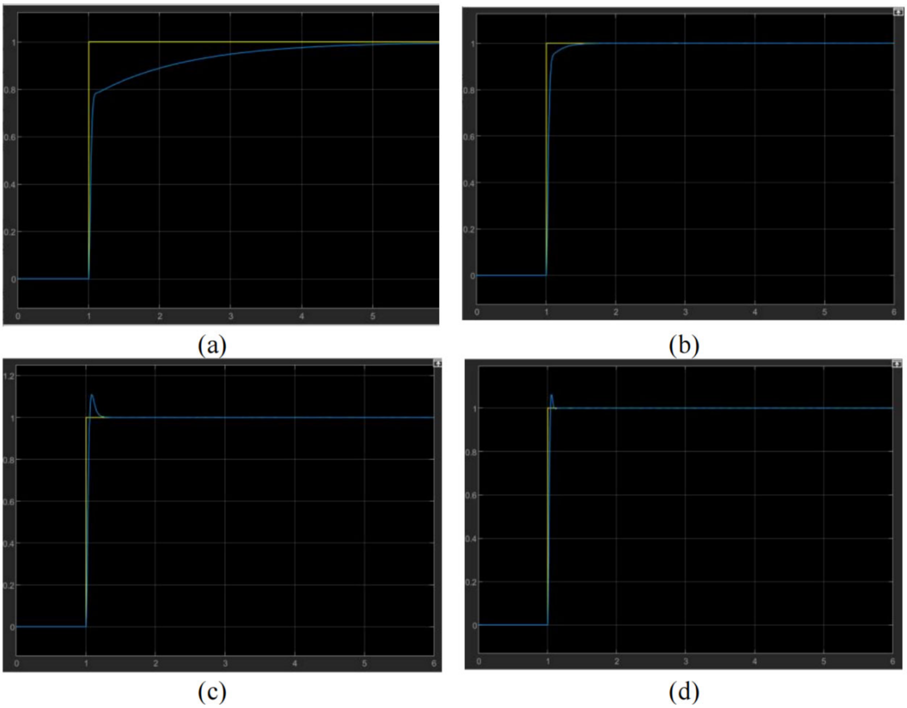

Fig. 4 Simulation results: (a) Kp=1, Kd=1; (b) Kp=10, Kd=1; (c) Kp=20, Kd=1; (d) Kp=20, Kd=1.8 (Photo credited: Original)

4 Simulation and Optimization of the Circuit

This work conducted further visual circuit simulations on Falstad, experimenting with different combinations of circuit components such as transistors, operational amplifiers, resistors, and capacitors to construct the DC motor and PD controller needed. This allowed us to analyze and determine the circuit's actual performance in a more comprehensive manner. In addition, with the tools provided by Falstad,the voltage and current could be observed at any point in the circuit, offering a more detailed insight into the circuit's behavior.

The traditional basic PD control typically uses a parallel connection of an inverting proportional operational amplifier and a differentiator to achieve the desired PD control effect. In this configuration, Kp is set to 20 and Kd to 1.8, which aligns with the optimal parameters previously obtained in Simulink.

After connecting this setup to a circuit with a transfer function of 3/(s+0.1*s^2), this work obtained the following simulation results in Falstad. The simulation results provided clear visual feedback, demonstrating the PD control system's effectiveness. The combination of Kp=20 and Kd=1.8 resulted in a fast response speed with minimal overshoot, validating our previous findings.

Further analysis revealed that the PD control model constructed in Falstad closely resembled the response curves obtained in Simulink, confirming the consistency and reliability of our tuning process. The visual circuit simulation provided a more intuitive understanding of the system's behavior, helping us refine the circuit design and parameter settings.

In addition to validating the optimal parameters, the Falstad simulation also allowed us to explore the impact of different component values on the PD controller's performance. By experimenting with different resistor and capacitor values in the differentiator and proportional amplifier circuits, this work gained deeper insights into their contributions to system stability, response speed, and overshoot control. Simulation results are shown in the Fig. 5:

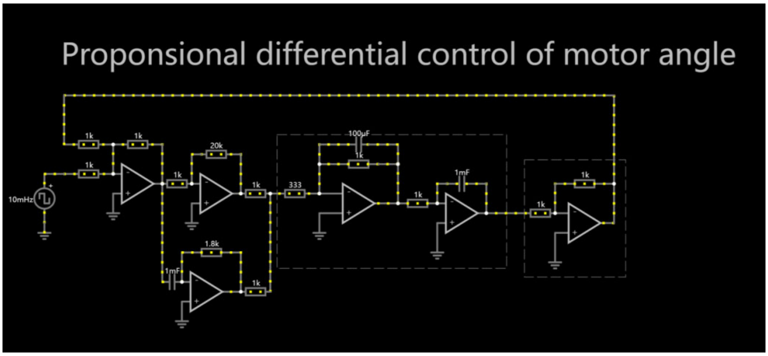

Fig. 5 Falstad simulation (Photo credited: Original)

The resulting simulation curve is shown in the Fig.6:

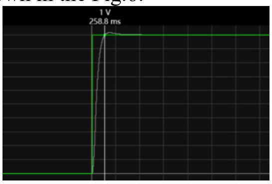

Fig. 6 Response curve (Photo credited: Original)

We can see that the response curve is similar to what this work obtained previously in Simulink, with a response speed of 258.8 milliseconds. This result demonstrates a high degree of consistency between the two simulation platforms, confirming that our traditional PD control model is effective in delivering rapid response times.

However, after replacing the traditional basic PD with an operational amplifier constructed by connecting an inductor and a resistor in series, this work obtained a new PD controller, as shown in Fig. 7. The calculation formula for the PD controller in this configuration is as follows:

$$\frac{V_{out}}{V_{in}} = -\frac{R2 + Ls}{R1} \tag{2}$$

$$\frac{V_{out}}{V_{in}} = -\left(\frac{R2}{R1} + \frac{L}{R1}s\right) \tag{3}$$

$$\frac{R2}{R1} = \frac{1000}{50} = 20 = K_p \qquad \frac{L}{R1} = \frac{90}{50} = 1.8 = K_d \tag{4}$$

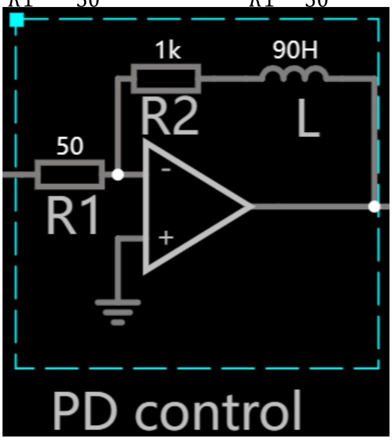

Fig. 7 PD controller (Photo credited: Original)

The final complete circuit diagram is shown in Fig. 8:

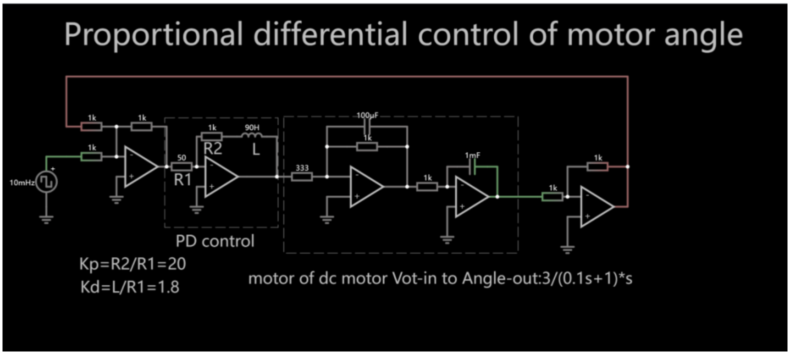

Fig. 8 The final complete circuit (Photo credited: Original)

The response curve obtained at this time is shown in Fig. 9:

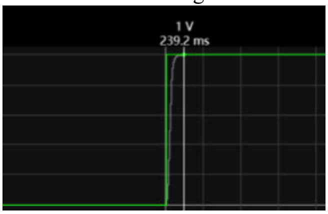

Fig. 9 Response curve (Photo credited: Original)

Compared to the response curve of the traditional PD control model, the response curve of the PD model used here not only successfully eliminates overshoot but also achieves a further improvement in response speed. Although the improvement in speed is not very significant, it clearly demonstrates that this PD model can maintain a fast response speed while reducing overshoot, achieving the desired results.

This successful outcome confirms the effectiveness of our approach and highlights the advantages of using an inductor-resistor series combination to form the operational amplifier. By achieving both speed and stability simultaneously, the optimized PD controller meets the performance expectations this work had set.

Furthermore, this improvement underlines the model's robustness and applicability to practical scenarios where response time and system stability are crucial. Despite the subtle degree of enhancement in response speed, the significant reduction in overshoot adds tremendous value to the system's performance, offering a reliable solution for DC motor speed control applications.

5 Discussion

Based on the experimental results of this paper, the new PD control model has demonstrated significant advantages in optimizing the response speed of DC motors [9]. However, there are still some aspects that warrant further discussion and improvement [10, 11]:

Parameter Tuning Strategy: Although the ideal parameter combination was obtained through simulation and experimentation in this paper, these parameters may not be suitable for all system configurations in practical applications. Future research could consider introducing adaptive tuning algorithms or intelligent optimization algorithms to achieve faster and more precise parameter adjustments.

Impact of Nonlinear Disturbances: The experimental conditions in this paper are relatively ideal and do not fully consider the nonlinear disturbances that may occur under actual working conditions, such as load changes and friction. Further research could explore compensation strategies for nonlinear disturbances to improve the robustness of the control system.

Multi-Objective Optimization: In addition to response speed and overshoot, DC motor system control also needs to consider multiple factors such as energy consumption, lifespan, and cost. In future research, multi-objective optimization strategies could be introduced into the design of the PD control system to achieve more comprehensive optimization.

Extension to Complex Systems: Although this paper focuses on the control of a single DC motor, in practical applications, motors often interact with other mechanical or electrical systems. In the future, the new PD control model could be extended and applied to more complex multi-motor collaborative or multi-axis linkage systems to verify its performance.

Nonlinear Compensation Strategies: Further research could investigate compensation strategies for nonlinear disturbances to improve the robustness of the control system. For instance, methods such as model predictive control, sliding mode control, or fuzzy logic control could be explored to enhance the system's ability to handle varying loads and other nonlinearities.

Integration with Other Controllers: The PD controller can be combined with other controllers like PI, PID, or advanced predictive controllers to further improve system performance. This hybrid approach could take advantage of the strengths of different control strategies, providing both quick response and steady-state accuracy.

Practical Implementation Considerations: When implementing the optimized PD control system in practical scenarios, hardware limitations and communication delays could introduce additional challenges. Therefore, strategies to mitigate these issues, such as the use of high-speed processors or robust communication protocols, should be considered.

6 Conclusion

This work presented an optimized PD control model designed to improve the response speed of DC motors. By meticulously tuning the PD parameters (Kp = 20, Kd = 1.8) through MATLAB/Simulink simulations, the model achieved an optimal balance between response speed and stability. The proposed PD control model effectively addressed the issues of slow response speed and overshoot inherent in traditional PD models. The results, validated through both Simulink and Falstad platforms, highlighted the model's effectiveness, achieving a rapid response speed of 258.8 milliseconds without overshoot.

Furthermore, by incorporating an inductor-resistor series combination in the PD controller, the improved model achieved further enhancements in speed while maintaining system stability. This confirmed the model's robustness and practicality for real-world DC motor speed control applications. Despite the subtle improvement in response speed, the significant reduction in overshoot adds considerable value to the system's overall performance.

However, further research is warranted to refine this model. Future work should focus on adaptive tuning algorithms, nonlinear disturbance compensation strategies, multi-objective optimization, and the integration of other control strategies to enhance system performance comprehensively. Ultimately, this study provides a practical and efficient optimization framework for PD-controlled DC motor speed regulation systems, offering fast response speed, reduced overshoot, and enhanced stability.

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