Research on the Stability of Output Speed of DC Motor based on PD Control

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Abstract. PD control, short for Proportional-Derivative control, is a type of feedback control where the control signal is a linear combination of two terms: proportional to the error signal (the difference between the desired setpoint and the actual output) and derivative of the error signal. It is a common method used in control systems to achieve desired performance in dynamic systems and is widely used in fields where precise and responsive control of dynamic systems is necessary. Common applications include (i) robotics, (ii) motion control systems, (iii) automotive aerospace and so on. This paper addresses the stability analysis of output speed control for DC motors, focusing on the application of Proportional-Derivative (PD) control. Given the significance of stable speed regulation in industrial settings, the research aims to investigate the stability characteristics of PD control and its implications for DC motor speed control systems. The study employs mathematical modeling and simulation techniques to analyze the stability of the PD control strategy, considering variations in proportional and derivative gains. Through simulations conducted using Tinkercad and Falstad, the effectiveness of PD control in maintaining desired speed outputs is evaluated, along with its robustness against disturbances. Nowadays, this work is pursuing for high-efficiency and thus low-delayed machine and even no-delay machine is the target we all want to chase. This paper mainly talks about how to get fast response with no steady state error and motivates the research in all kinds of applications using PD control systems and this research contributes to a deeper understanding of PD control in DC motor speed regulation and provides insights for designing reliable control systems in industrial applications, such as robotics automation and artificial system.

Keywords: PD Control System, Falstad, Tinkercad

1 Introduction

The efficient control of output speed in DC motors is essential across various industrial applications, where precise speed regulation is paramount for optimal performance. Proportional-Derivative (PD) control stands out as a promising method for achieving stability in speed control systems. In this context, this research delves into the stability analysis of output speed control for DC motors utilizing PD control. The fundamental question driving this investigation is: How does PD control

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contribute to the stability of output speed regulation in DC motors, and what are the implications for industrial applications requiring precise speed control.

Among various control techniques, Proportional-Derivative (PD) control stands out as a widely utilized method for its simplicity and effectiveness in achieving stability and responsiveness. For proportional (P) term, the output is directly proportional to the current error signal. Mathematically, we can express the term as: $P(t) = K_p \cdot e(t)$. And for derivative(D) term, $D(t) = K_d \cdot \frac{de(t)}{dt}$. Actually, this study also have I term, which can be expressed as $I(t) = K_i \cdot \int e(t)\,dt$. So, there is a PID controller $u(t) = K_p \cdot e(t) + K_i \cdot \int e(t)\,dt + K_d \cdot \frac{de(t)}{dt}$. We can see that the derivate the PI control, its formula is exactly the same as PD. The PI control will be mentioned in the later part. Now consider PD control, by using feedback from both the current speed error (proportional term) and its rate of change (derivative term), PD control offers a straightforward yet powerful approach to regulating motor speed. However, the stability characteristics of PD control systems are influenced by factors such as controller gains, system dynamics, and external disturbances, necessitating a thorough analysis to ensure robust performance.

Previous studies by Suwandi etc have explored to design and implementation of adaptive PID controller for speed control of DC motor, highlighting the importance of stability analysis in ensuring reliable performance [1, 2]. Research of Yassine etc also give me the inspiration of the PI controller [3]. Additionally, research by Kisshore helps to understand the more complex concept [4]. Salmon etc show the stability and performance evaluation of the speed control of DC Motor [5, 6]. These works underscore the significance of investigating the stability characteristics of PD control in DC motor speed regulation.

Drawing upon the extensive literature available, this study aims to delve deeper into the stability of PD control when applied to output speed regulation for DC motors [7-10]. The prime focus is to meticulously analyze the stability characteristics of PD control and its potential implications in practical applications, thereby contributing to the advancement of motor control techniques. To achieve this, the study will initially establish a solid foundation by reviewing the theoretical background of PD control, its principles, and the underlying mathematical frameworks. This will serve as a prerequisite for understanding the intricacies involved in stability analysis. Additionally, the study will explore the characteristics of DC motors, highlighting their working mechanisms and the challenges posed by speed regulation. Next, the research will embark on mathematical modeling, simulation, and analysis to assess the effectiveness of PD control in maintaining desired speed outputs. This will involve the careful selection of controller parameters and the exploration of their impact on stability. Through rigorous simulations, the study will evaluate the performance of PD control under various operating conditions, including varying loads and disturbances. To complement the theoretical analysis, the study will also delve into related device and material considerations. This will include the selection of suitable components for the circuit, such as resistors, capacitors, and inductors, and the exploration of their impact on the overall system performance. Furthermore, the methodology employed for stability analysis will be comprehensively outlined. This will cover the techniques used to assess the stability of the PD controller, including frequency domain analysis, time domain simulations, and other relevant approaches. The study will also highlight the advantages and limitations of each technique, enabling a comprehensive understanding of the stability analysis process. The simulation setup will be meticulously described, emphasizing the use of Tinkercad for modeling the circuit and Falstad for simulating the circuit. These tools will be leveraged to create a virtual representation of the DC motor control system, allowing for the exploration of various scenarios and parameter configurations. The study will explain the steps involved in setting up the simulations, including the selection of appropriate models, the definition of system parameters, and the configuration of the simulation environment.

Overall, this study aims to provide a comprehensive analysis of the stability of PD control in DC motor speed regulation. By combining theoretical insights, mathematical modeling, simulation analysis, and practical considerations, the study aims to contribute significantly to the field of motor control, enabling the development of more robust and efficient systems.

2 Methods and Materials

2.1 LM741 Operational Amplifier

To obtain the proportional and derivative gain K_p and K_d, a vital component amplifier is taken into use. For this paper, LM741 is used. Below is the illustration of typical application of LM741. As a general-purpose operational amplifier, the LM741 is employed in a diverse range of applications spanning from signal processing and instrumentation to audio amplification and control systems. Its enduring popularity can be attributed to its robust performance, cost-effectiveness, and widespread availability. The LM741 op-amp is housed in an 8-pin dual in-line package (DIP) and features a single operational amplifier with high input impedance, low input offset voltage, and high gain bandwidth product. These characteristics make it well-suited for amplification tasks, voltage regulation, filtering, and various other signal processing functions.

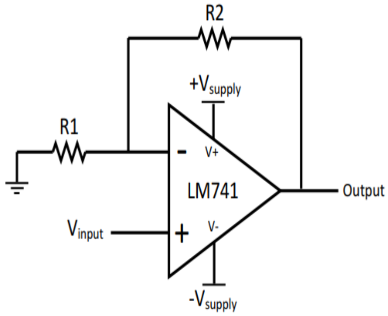


Fig. 1 Typical application of amplifier [1]

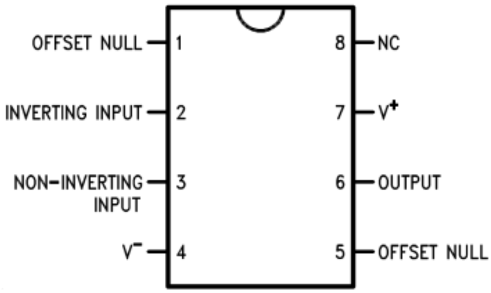


Fig. 2 Configuration of 8-pin CDIP or PDIP top view of LM741 [1]

Fig. 1 and Fig. 2 shows the typical application of amplifier and the configuration of LM741, respectively. Using KCL, we know that $\frac{0-V_{input}}{R_1}=\frac{V_{input}-V_{output}}{R_2}$. So $\frac{V_{output}}{V_{input}}=1+\frac{R_2}{R_1}$. This formula is useful when you want to set a specific gain.

2.2 Using Falstad to Simulate the Circuit

Falstad is an online circuit simulator that allows users to design, simulate, and analyze electronic circuits in real-time. It provides us with the opportunity to get easy access to simulate the circuit that we are researching on. Also, Falstad provides a virtual environment where users can design and simulate electronic circuits without the need for physical components which is very convenient for the study of this research.

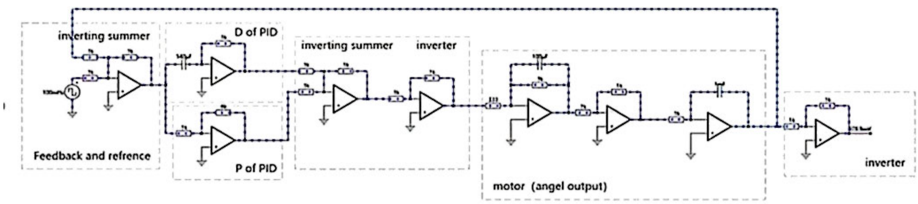


Fig. 3 Illustration of Falstad simulation (Photo credited: Original)

Fig. 3 shows the circuit we need to simulate. The D part of the PD control consists of a capacitor, an inverting amplifier and resistance, while the P part consists of an inverting amplifier and two resistances. This process sets the required parameters K_d and K_p we want. Electrical impedance. In D part, utilizing the method we talked in the amplifier part, $\frac{0-V_{input}}{Z_1}=\frac{V_{output}-0}{Z_2}$. Z represents electrical impedance which is useful in analyzing the circuit consists of resistance, inductor, and capacitor. For this, Z_1 is capacitor and Z_2 is resistor. This equation doesn't seem to have derivative part. So, we should use the current $I = C \cdot \frac{dU}{dt}$ to represents the LHS part of the equation. Finally, we get $\frac{V_{output}}{V_{input}} = RC \cdot \frac{dU}{dt}$. We can see that K_d is actually RC.

After getting the both the P and D parts, we use an inverting amplifier to invert the sign. This PD control should utilize 3 inverting amplifiers. Is there any way to reduce the complexity of the circuit? Let's try PI control which will get the similar result as well.

Instead of parallel circuit form, PI control uses a resistor in series with an inductor in the Z_2 section which will also result in a similar transfer function as the method one and should get the similar plot. Fig. 4, Fig .5 and Fig. 6 shows the D part of the PD control, P part of the PD control and PI control, respectively.

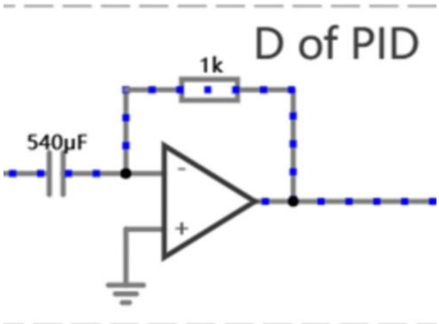


Fig. 4 D part of the PD control (Photo credited: Original)

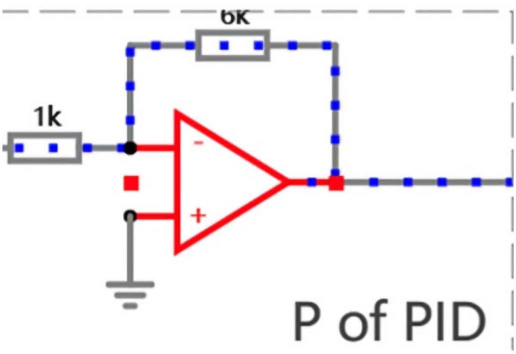


Fig. 5 P part of the PD control(Photo credited: Original)

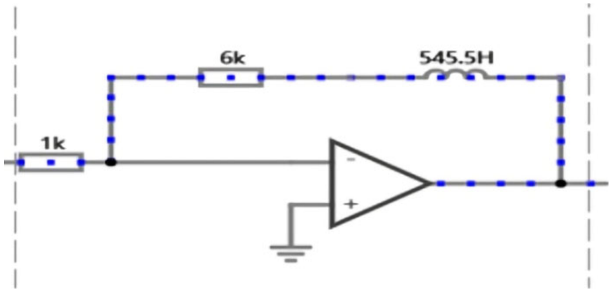


Fig. 6 PI control (Photo credited: Original)

2.3 Tinkercad to Build the Circuit

Tinkercad is an online platform primarily designed for 3D modeling and electronics projects. It offers intuitive tools that allow users to create 3D designs, simulate electronic circuits, and even develop basic code for microcontrollers. Overall, tinkercad serves as a versatile tool for design, prototyping, and learning.

During simulation, the graph of signal input and output will be observed, and we can adjust the parameters of each electrical elements to observe the graph or just copy the parameters using in the Falstad.

Fig. 7 and Fig. 8 show the circuit layout in Tinkercad. Initially, we considered it is relatively easy to build such a model on the Tinkercad because we already have the blueprint on the Falstad. However, we did confront with a big problem when we tested it. At first, we just thought that some wires were wrong, then we supposed that too many ops will make the system crash for the limited RAM. In the end, after a huge amount of trials we finally discover that is the capacitor caused the problem. The original capacity couldn't bear such strong signal mixed with feedback.

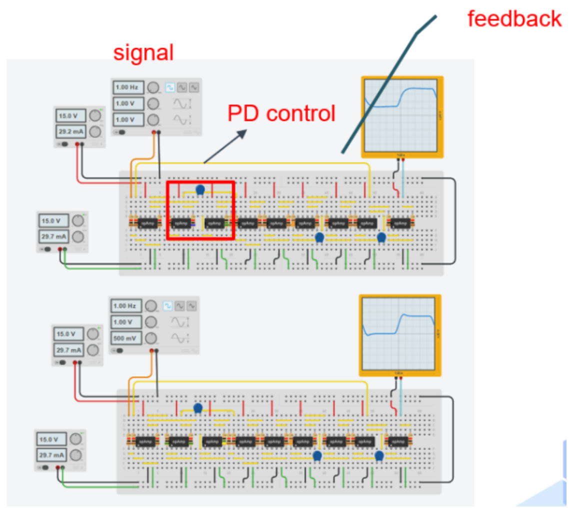
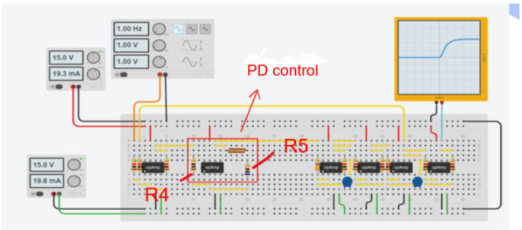


Fig. 7 PD circuit in Tinkercad (Photo credited: Original)



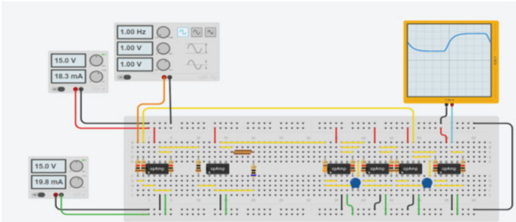


Fig. 8 PI circuit in Tinkercad(Photo credited: Original)

3 Results

Increasing the proportional gain K_p generally leads to a faster response time of the system. This is because the proportional term in the control signal is directly proportional to the error signal, causing a larger corrective action for a given error. However, it can also lead to an increase in overshoot and oscillations, which may introduce steady-state error. So, during the research, key point is to set and adjust the parameter.

Because kp is too big, the output of the op amp will exceed the upper limit of 15V, and if kp is too small, it will be too slow, so it is necessary to slowly increase kp to just under 15V, at this time the maximum output is 14.8V, which is just not exceeded, and then at this time to find the appropriate kd to make the circuit response speed the fastest and the steady-state error the smallest. The fastest and most stable value is kp=6, kd=0.78, but the best value is kp=10 when there is an overshoot. In Fig. 9, we know that the circuit gets response with no steady state error within around 0.3s.

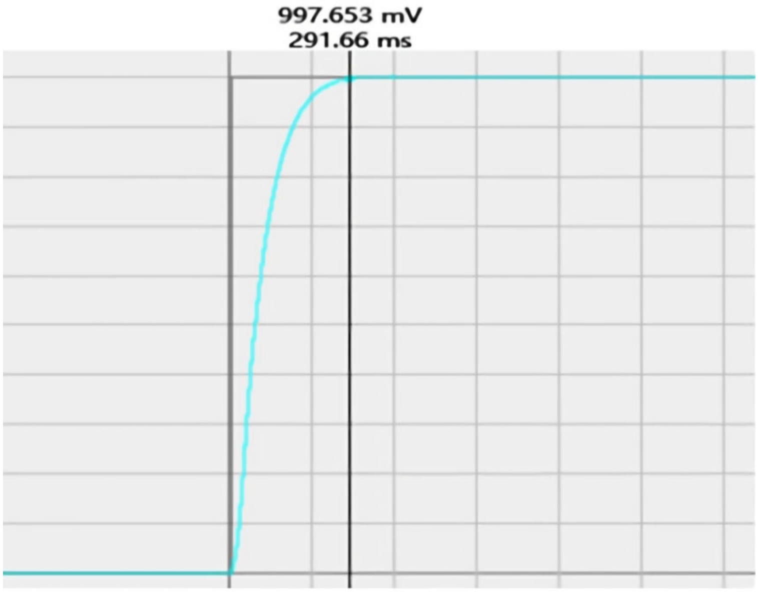


Fig. 9 Simulation figure of the circuit (Photo credited: Original)

4 Conclusion

The findings of this study contribute to a deeper understanding of PD control in DC motor speed regulation and provide valuable insights for designing stable and reliable control systems. The illustrations created using Tinkercad and Falstad further enhance the comprehension of the control system's behavior and facilitate visualization of theoretical concepts. In conclusion, this research has explored the stability of output speed control for DC motors utilizing Proportional-Derivative (PD) and Proportional-Integral (PI) control. Through mathematical modeling, simulation, and analysis, this study has investigated the stability characteristics of the PD control strategy and its implications for practical applications. In the future, related research could explore advanced control strategies, such as adaptive control or nonlinear control techniques, to further enhance the stability and performance of DC motor speed control systems. Additionally, investigating real-time implementation considerations and practical challenges in industrial applications will be crucial for the successful deployment of PD control in real-world scenarios. In summary, the stability analysis presented in this paper underscores the effectiveness of PD control in achieving stable output speed control for DC motors, laying a foundation for the development of robust and efficient control systems in various industrial and automation applications.

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