Comparative study on PID for DC motor speed regulation

Xiangda Han*

School of Electrical Engineering, Hebei University of Architecture, 075051 Zhangjiakou, China

Abstract. Because of its straightforward design and excellent adjustment efficiency, PID (proportional-integral-derivative) controllers are frequently employed in motor speed control. This study reviews the use of PID control technology in DC motor speed regulation, analyses DC motor speed regulation, and compares various proportional integral derivative (PID) speed regulation techniques. In this paper, the key role of PID parameter optimization in improving the response speed and accuracy of the system is analyzed and pointed out. The optimal technique for delivering a dynamic response to load disturbances and manageable overshoots is the modified Ziegler-Nichols modulation approach. The CHR regulation method is poor in dynamic response, while the Tyreus-Luyben regulation method is better in dynamic response to load interference, but the overshoot is small. Finally, the damped oscillation regulation method shows a higher stability time in the absence of overshoot. Proper proportional, integral and differential values of the tuned PID controller are essential for process control.

Keywords: PID control, closed-loop control, DC motor, automatic control.

1 Introduction

DC motor usage in the industrial control industry has increased recently. When it comes to controlling speed, dc motors are incredibly adaptable. High-performance DC motor drivers are extensively utilized in industrial settings due to their robust initial torque, rapid acceleration, and deceleration capabilities, straightforward linear control mechanisms, and swift response characteristics. Among its many uses are in bridge cranes, rolling mills, cutting tools, robot operators, guided vehicles, electric traction, and other fields. DC motors are highly controllable electric actuators. In recent years, DC motor drives have been considered simpler and more cost-effective compared to AC drives, leading to their widespread adoption in industrial control applications. DC motors offer a high degree of versatility and flexibility when it comes to speed regulation. DC motor drivers with high performance are favored in industrial use for their superior initial torque, quick acceleration and deceleration, responsive operation, rapid braking, and simplified linear control. Robot operators, guided vehicles, cutters, overhead cranes, electric traction, and many other applications use DC

* Corresponding author:1811030109@stu.hrbust.edu.cn

motors, which are highly adjustable electric regulators.DC electrically powered drives are more affordable and straightforward than AC drives[1]. Among many control technologies, proportional Integral-differential (PID) controller has become the first choice for DC motor speed regulation because of its simple operation and superior regulation performance. This technology is essential for raising product quality, cutting energy use, and increasing manufacturing efficiency.Internationally, research on PID control systems covers parameter optimization, adaptive strengthening, and the ability to cope with complex conditions. Researchers are actively exploring advanced control strategies such as integrated fuzzy logic, adaptive algorithm and neural network technology to improve the performance of PID systems. In addition, academic teams in different countries have made important advances in PID applications adapted to extreme environments and non-standard operating conditions. This paper will comprehensively review the PID control technology in DC motor speed regulation, and analyze the latest progress in theoretical research and practical application at home and abroad. Through the analysis and comparison of different research methods and results at home and abroad, this paper aims to provide in-depth insights for the design and optimization of motor control systems.

2 Four control methods are introduced

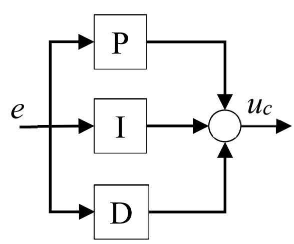

Fig. 1. （a） Closed loop control chart[4]

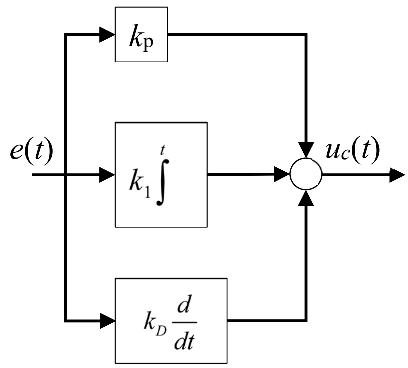

Fig. 1. （b）Time domain operator form[4]

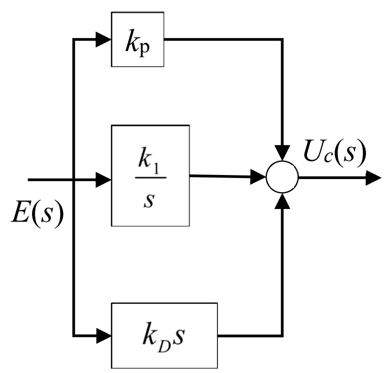

Fig. 1. （c）Laplace transform form[4]

Control systems are dominated by PID controllers. For instance, it was used in more than 95% of the controlling loops in control systems applications by the middle of the 20th century.[2]The simplicity and excellence of PID controllers to handle a wide range of processes, if not optimal, have made them excellent in many applications and have become standard controllers in industrial Settings.[3]The initial letter of each component that makes up the conventional triathlon controller is represented by the acronym PID. In the controller, "P" stands for proportional elements, "I" for integral elements, and "D" for derivative elements. PID or tri-mode controllers are most likely the most popular controllers in industrial settings.It is possible for a control network with a PID control module at its center to be a part of an intricate industrial control system.

Withstood technological advancements from the analog period to the digital computer control systems era, three-stage PID control devices have a lengthy history of use.In the high-volume market typical of the procedure industry, it continues to be the first and sole controller for mass production.The technical success of the feedback management system in the engineering industry is based on how well it performs when utilizing the Laplace transform analysis. Through the Laplace transform integrator and the simple representation of the differentiator using [s], it greatly helps to analyze the theoretical basis of PID control performance. Conceptually, PID controllers are quite complex and can be given three different representations.Initially, each of the three conditions can be designated in order to perform some specific control action in a form that is symbolic (Figure 1(a)). The time-domain format operator shape (Figure 2(b)) is next, and lastly the PID controller's Laplace transform form (Figure 2(c)). This allows the relationship between time, space, and velocity to be discussed with the capabilities of the PID controller and provides an explanation of how it operates in s-domain operation.[4] Pied controllers can be tuned using a variety of techniques, such as the Ziegler-Nichols approach, manual tuning, and MATLAB adjustment.[5] High-level activities are suited for the（proportional-integral-derivative）controller. The findings demonstrate that, within the allowable overshoot range, the four enhanced Ziegler-Nichols method techniques offer a more dynamic target system response.The research has a certain reference value for the design and application of industrial control system in the comparative study of PID controller to DC motor speed regulation. This paper analyzes the performance indexes of PID controller, including absolute error integral (IAE), square error integral (ISE), time times square error integral (ITSE) and time times absolute error integral (ITAE). These indicators are utilized to assess the（proportional-integral-derivative）controller's performance and are crucial to the control system's cost function. Modified (ZN) adjustment method, (CHR) adjustment method, (TL) adjustment method and Damped Oscillation adjustment method. The PID controller's effectiveness in controlling the speed of DC electric motors was compared in various ways. Every one of these several PID controller regulation techniques has benefits and drawbacks of its own.

3 Four methods of regulation

3.1 Ziegler-Nichols method

Ziegler-Nichols regulation method is a commonly used PID controller regulation method, and its transfer function is shown in Formula 1[6], which is used for process control in industrial applications. The optimal control of the system response is achieved by adjusting the ratio, integral and differential values[7]. This method has wide application and importance in engineering control. Its advantages are simple and easy to operate, suitable for many industrial control processes, and robust. Nonetheless, the drawbacks include the challenge of tuning higher-order, time-delayed, and nonlinear systems, and the fixed-gain feedback controller's inability to deliver the desired control performance across a broad spectrum of operational circumstances. In addition, this method may cause the system to overshoot.

$$G(s)= e^{-Ls}\frac{k}{1+Ts} \tag{1}$$

3.2 Tyreus-Luyben method

This method, which is an enhanced approach for PID controller tuning, akin to the Ziegler-Nichols method but resulting in a distinct final controller configuration. This method exclusively provides the settings for PI and PID controllers, aiming to diminish oscillatory effects and enhance robustness. Its transfer function is depicted in formula 2.[6] The method depends on the ultimate gain and period. However, this approach is time-consuming and, like the Ziegler-Nichols approach, forces the system to the edge of instability. This modulation approach has the advantage of generally improving resilience and reducing oscillatory impacts.It provides Settings for both PI and PID controllers and shows low overshoot, low dynamic load interference response in practical implementation. However, the disadvantage of this method is that it is time-consuming and can easily lead to system instability.

$$G_c(s) = K_c\left(1+\frac{1}{\tau_i s}+\tau_d s\right) \tag{2}$$

3.3 Chien-Hrones-Reswick method

The (CHR) adjustment method is a PID controller adjustment method whose transfer function is shown in Formula 3 to improve set point adjustment and interference rejection.[8] For setpoint adjustment and interference suppression, it comes in two qualitative specifications: the fastest reaction with no overshoot and the quickest reaction with 20% overshoot. In practical implementation, the CHR regulation method shows slower dynamic response and longer stabilization time, but with lower overshoot and lower static error.The advantage of the Chien-Hrones-Reswick (CHR) method is that it provides high set point tracking performance with low overshoot and steady-state error. In addition, it can also improve the ability to suppress interference. However, the disadvantage of the CHR method is that it performs poorly in terms of dynamic response, with long adjustment time and low performance index. In contrast, the Modified Ziegler-Nichols and Tyreus-Luyben conditioning methods perform better in some aspects.

$$G(s)=\frac{K}{(T_S+1)(L_S+1)} \tag{3}$$

3.4 Damped Oscillation method

The Damped Oscillation regulation method is also a damping oscillation regulation method. Its transfer function is shown in formula 4[9], and it is a method for PID controller adjustment designed to solve the stability problem of a system that does not allow continuous oscillations. This method achieves damped oscillation by adjusting the proportional gain until a response curve with a 1/4 attenuation ratio is obtained. The method provides PID controller parameters for setpoint adjustment and interference suppression. The damped oscillation regulation method is a method for PID controller regulation, which aims to solve the stability problem of continuous oscillation in some process control systems. This method is a slight modification of the standard regulation procedure by adjusting the gain until a response curve with a 1/4 attenuation ratio is obtained. The controller parameters of the damping oscillation regulation method are as follows:

Table 1. Controller parameters of damping oscillation regulation method [10].

Controller category	Kp	Ti	Td
P	1.1Ku	-	-
PI	1.1Ku	Pu/2.6	-
PID	1.1Ku	Pu/3.6	Pu/9

As shown in Table 1, this method of regulation is suitable for processes that do not allow continuous oscillations and need to solve stability problems.The system's efficiency and reliability can be enhanced by modifying a controller's parameters.

The advantages of this method include the ability to provide a stable response curve, reduce the overimpulse of the system, and have a better dynamic response to load interference. However, The damped oscillation regulation method is complex and requires additional experiments and system debugging. It may also lead to longer adjustment times, making it unsuitable for certain applications.In general, the damped oscillation regulation method may show better performance in some specific control systems, but in other cases it may be necessary to weigh its advantages and disadvantages.

4 Comparison of four adjustment methods

Table 2. Comparison of response results[7].

Adjustment method	Tr (s) rise time	T (s) time constant	Mp overshoot	Ess steady-state error	On-load speed (rpm) load speed
Ziegler-Nichols method	0.0571	0.874	74.56	0.009	999.991
The Chien-Hrones-Reswick method sets a 20% overshoot	0.0583	1.66	1.66	0.002	1002
Tyreus-Luyben method	0.0573	0.714	0.714	0.0012	998.8
Damped Oscillation method	0.0578	0.0578	0.02	0.002	1002

Based on the information shown in Table 2, it is evident that:

Ziegler-Nichols method has the fastest rise time Tr, but the maximum overshoot Mp is relatively high, the steady-state error Ess is very small, and the no-load speed is close to 1000 RPM.The setting time Ts of CHR setpoint 20% overshoot method is long, the maximum overshoot Mp is low, the steady-state error Ess is very small, and the no-load speed is slightly higher than 1000 RPM.The setting time Ts of Tyreus Luyben method is short, the maximum overshoot Mp is moderate, the steady-state error Ess is small, and the no-load speed is slightly lower than 1000 RPM.The rise time Tr of Damped Oscillation is the same as the setting time Ts, and the maximum overshoot Mp is very small Based on the above four data analyses, the Modified Ziegler-Nichols adjustment method may be the most appropriate choice if a fast response and an acceptable amount of overshoot are considered. On the other hand, if the system has higher requirements for steady-state performance and lower overshoot, then the Chien-Hrones-Reswick adjustment method may be more suitable. The Tyreus-Luyben tuning method is appropriate for systems demanding a swift response, minimal overshoot, and low steady-state error. Ultimately, the Damped Oscillation tuning method is suitable for systems requiring a rapid response, reduced overshoot, and high steady-state accuracy.

For example, for DC motor control systems that require fast response and acceptable overshoots, such as industrial motor systems that require fast and precise control, such as fan control, conveyor belt control, etc. Modified (ZN) control technology modification can be the best option. The (CHR) regulation approach might be more appropriate for DC motor control systems that have high constant state efficiency requirements along with low overshoot requirements, such as those systems.

The TL regulation technique is appropriate for DC motor control systems that need to have steady-state mistakes, reduced overshoot, and quick response times. In conclusion, the damping oscillation adjustment method works well for DC motor control systems that need to respond quickly, have minimal overshoot, and maintain high steady-state accuracy. This includes motor control scenarios that need to respond quickly, have minimal overshoot, and maintain high constant state accuracy.

Table 3. Performance index [10].

adjustment method	ISE	IAE	ITAE	ITSE
Ziegler-Nichols method	871.2	20.54	5.98	173.4
The Chien-Hrones-Reswick method sets a 20% overshoot	256.5	7.121	4.978	7.853
Tyreus-Luyben method	285.4	7.772	2.327	11.2
Damped Oscillation method	252.4	4.812	2.721	5.002

According to Table 3, the ISE, IAE, ITAE and ITSE values of the Damped Oscillation regulation method are the lowest, which indicates that the damped oscillation regulation method has the best overall performance on these performance indexes. Low performance indices usually mean better control system performance because they indicate a smaller cumulative value of errors.

Based on the above analysis,when selecting a regulation method, engineers need to consider the specific requirements and performance indicators of the system, such as response time, overshoot, and steady-state error.

The improved ZN method may be more suitable for applications with higher response speed requirements, while the CHR method may be more suitable for applications with higher steady-state performance requirements.

The TL method may be a compromise choice, which provides a faster response and a smaller overshoot, and is suitable for systems with certain requirements for both.
The Damped Oscillation method may be suitable for systems with high stability requirements, although it may require more commissioning time and experimentation.

5 Conclusion

The optimal technique for delivering a dynamic response to load disturbances and manageable overshoots is the modified Ziegler-Nichols modulation approach. The CHR regulation method is poor in dynamic response, while the Tyreus-Luyben regulation method is better in dynamic response to load interference, but the overshoot is small. Finally, the damped oscillation regulation method shows a higher stability time in the absence of overshoot. These results have important reference significance for PID controller selection and adjustment in industrial applications.Selecting the right regulation strategy is crucial to enhancing the stability and effectiveness of the control system since the PID controller's performance is crucial to industrial process control. PID controller shows a good control method in controlling the speed of DC motor under load interference.To further enhance the control ability of the system design, however, future study might take into account the application of adaptive PID controllers.

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