Available Online: 27 May 2025 DOI: 10.54254/2977-3903/2025.23523

Study on load disturbance rejection of PID control in DC motor speed regulation systems

Siyuan Chen

Beijing University of Civil Engineering and Architecture, Beijing, China

yuanyi10585915@163.com

Abstract. This paper investigates the issue of load disturbances in DC motor speed regulation systems. In response to the limited disturbance rejection capability of traditional PID controllers, a PID controller with feedforward compensation is designed. The study first analyzes the dynamic impact mechanism of sudden load changes on motor speed, and then achieves precise control of the DC motor using PWM technology. Through comparative analysis of simulation and experimental results, the proposed feedforward-compensated PID control demonstrates significant improvements in dynamic response speed, overshoot, and steady-state accuracy compared to traditional PID control. The findings indicate that the proposed control strategy effectively suppresses load disturbances, enhances system stability and robustness, and offers valuable insights for practical engineering applications.

Keywords: PID control, feedforward compensation, PWM speed regulation, load disturbance

1. Introduction

In DC motor speed regulation systems [1], load disturbance is one of the primary factors affecting system stability and dynamic performance. Sudden changes in load often cause severe fluctuations in motor speed, which in turn compromise the control accuracy and operational reliability of the entire system. Therefore, how to effectively suppress the impact of load disturbances on DC motor speed has become a key issue in improving the performance of speed regulation systems. Traditional PID controllers are widely used in DC motor control due to their simple structure and ease of parameter tuning. However, when confronted with abrupt load changes, pure PID control often exhibits delayed response and significant overshoot, making it difficult to achieve ideal dynamic performance.

To address this issue, this study introduces a feedforward compensation strategy based on classical PID control, aiming to enhance the system's capability to rapidly suppress load disturbances. Feedforward compensation enables preemptive correction of the control signal based on known or predicted disturbance information, thereby significantly improving the robustness and responsiveness of the motor speed regulation system. This paper establishes a mathematical model of the DC motor, analyzes the dynamic mechanism of speed variation under load changes, and designs and implements a PID controller with feedforward compensation. Combined with pulse-width modulation (PWM) technology to drive the DC motor, the system's dynamic performance under load disturbances is validated through both simulation and experimental testing. The study compares and analyzes the response characteristics of pure PID control and feedforward-compensated PID control, including overshoot, settling time, and steady-state error, to comprehensively evaluate their disturbance rejection effectiveness.

This research is not only of practical significance in enhancing the stability and responsiveness of DC motor speed regulation systems but also provides theoretical support and practical reference for motor control in industrial scenarios involving rapid load changes. By conducting an in-depth analysis of the load disturbance rejection mechanism and optimizing control methods, the study offers more efficient and reliable technical solutions for applications in intelligent manufacturing, automation equipment, and other related fields.

2. Project background and significance

With the rapid development of industrial automation and intelligent manufacturing technologies, increasing performance demands have been placed on motor speed regulation systems. Due to their excellent speed control capabilities, simple control structure, and high starting torque, DC motors have been widely applied in various industrial equipment, automatic control systems, and robotics. However, in practical applications, load disturbances are inevitable and often occur as abrupt or rapid changes, severely affecting the stability and control accuracy of DC motor speed. Particularly in scenarios with high demands for dynamic response and stability—such as CNC machine tools, automated production lines, and intelligent transportation systems—the ability of the motor to quickly adapt to load variations has become a critical indicator of overall system performance.

Traditional PID controllers are widely used in DC motor speed regulation due to their simple implementation, but they often struggle under conditions of severe or frequent load disturbances. These controllers typically suffer from response delays, long regulation times, and significant overshoot, making them inadequate for high-performance control requirements. As such, improving the dynamic performance and robustness of DC motor speed regulation systems under load disturbances has become a crucial research focus in the field of motor control.

To address this challenge, this project introduces feedforward compensation technology based on classical PID control. By predicting and compensating for load disturbances, the control signal can be adjusted in advance to reduce response delays and enhance the system's capability to suppress load variations. The effective integration of feedforward and feedback control can significantly improve the dynamic characteristics and steady-state precision of motor speed regulation systems without increasing system complexity.

The research conducted in this project is of both theoretical and practical significance. It contributes to a deeper understanding of the mechanism by which load disturbances affect control systems and the optimization of related strategies. Additionally, it holds considerable engineering value. By designing and implementing a PID controller with feedforward compensation, the stability, response speed, and disturbance rejection capability of DC motor systems can be greatly improved [2], providing a theoretical foundation and technical support for the development of high-performance motor drive systems. This, in turn, can positively impact the advancement of intelligent manufacturing, precision machining, modern logistics, and other industries.

3. Research methodology

This study adopts a comprehensive approach that integrates theoretical analysis, system modeling, controller design [3], and experimental validation. The specific steps are as follows:

3.1. Theoretical modeling and analysis

First, a mathematical model of the DC motor is established, including the electrical and mechanical equations, to analyze the system's dynamic response characteristics under various load disturbances. Through small-signal linearization, the transfer function of the system is derived to clarify the mechanism by which load variations affect rotational speed.

Electrical Equation (Armature Circuit):

$$u(t) = L\frac{di_a(t)}{dt} + Ri_a(t) + e(t), e(t) = K_e\omega(t) \tag{1}$$

Mechanical Equation (Rotational System):

$$J\frac{d\omega(t)}{dt} + B\omega(t) = K_T i_a(t) - T_L(t) \tag{2}$$

After small-signal linearization and Laplace transformation:

$$U(s) = (Ls + R)I_a(s) + K_e\Omega(s) \tag{3}$$

$$Js\Omega(s) + B\Omega(s) = K_t I_a(s) - T_L(s) \tag{4}$$

The derived transfer function of the system (without disturbance) is:

$$G(s) = \frac{\Omega(s)}{U(s)} = \frac{K_t}{(LJ)s^2 + (LB + RJ)s + (RB + K_e K_t)} \tag{5}$$

3.2. Controller design

Based on the conventional PID control framework, a feedforward compensation module is introduced [4], as shown in Figure 1. The feedforward path is designed according to predicted load variations, enabling pre-adjustment of the control signal to reduce the impact of sudden load changes on system output. Through theoretical derivation and simulation, optimal configurations for PID parameters and feedforward gains are determined.

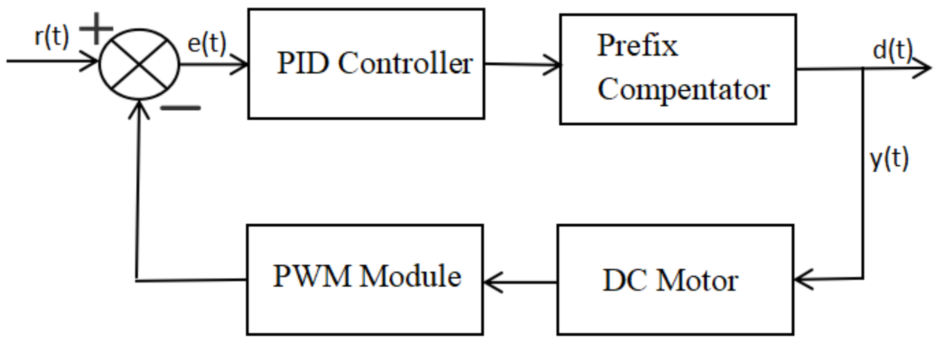

Figure 1. Feedforward compensation module integration

PID Feedback Control: Corrects errors and ensures reference tracking.

Feedforward Compensation: Pre-adjusts the control signal based on estimated load disturbances to mitigate their impact. Both PID parametersK_p、K_i、K_d and feedforward gain K_{ff} are tuned via theoretical derivation and simulation.

Complete Transfer Function with Disturbance and Feedforward Compensation:

The system output with feedforward compensation is given by:

$$\Omega(s) = \frac{G(s)C(s)}{1+G(s)C(s)} U_r(s) + \left(\frac{G(s)C(s)F(s)}{1+G(s)C(s)}\right) T_L(s) \tag{6}$$

G(s): Transfer function of the motor

C(s): Transfer function of the PID controller

F(s): Transfer function of the feedforward compensator

The design objective is to ensure F(s) ≈ 1/C(s); at low frequencies, this simplifies to F(s) = 1/Kp.

3.3. PWM control and system implementation

PWM (Pulse Width Modulation) technology is employed to achieve continuous and controllable input voltage for the DC motor, enabling precise speed regulation. The system hardware is built on a microcontroller or DSP platform [5], which executes the control algorithm in real time.

1) The controller output is converted into a PWM duty cycle.
2) The microcontroller or DSP platform generates the PWM signal in real time.
3) The motor is driven via power devices (e.g., MOSFETs) to realize accurate speed control.

3.4. Simulation and experimental validation

A system simulation platform is constructed using MATLAB/Simulink to test the dynamic response under various load disturbances, evaluating the robustness and performance metrics of the controller. Experimental validation is subsequently conducted on a physical hardware platform, comparing system performance with and without feedforward compensation under sudden load changes. Particular attention is paid to overshoot, settling time, and steady-state error. Recommended performance metrics are listed in Table 1:

Table 1. Recommended performance metrics

Metric	Recommended Value	Description
Overshoot (%)	≤ 5%	Ensures smooth response without severe fluctuation
Settling Time (2%)	≤ 2 s	Enables rapid system convergence
Steady-State Error	≈ 0	Eliminated by integral action
Phase Margin	≥ 45°	Ensures system stability
Gain Margin	≥ 6 dB	Enhances robustness

4. Problems identified in the study and proposed solutions

4.1. Difficulty in modeling load disturbances

In practice, load variations are often uncertain and nonlinear, making accurate modeling of load disturbances challenging. If the feedforward compensation model fails to predict the load accurately, the effectiveness of the compensation may be limited, and even introduce new system errors.

Proposed Solutions:

1) Improved Load Disturbance Estimation: Employ more accurate estimation techniques for load disturbances. For example, real-time measurements or historical data analysis, combined with filters such as the Kalman filter, can be used to estimate load disturbances in real time and accordingly adjust the feedforward compensator.

2) Adaptive Control Strategy: Design an adaptive controller that adjusts the compensation gain of the feedforward compensator based on real-time disturbance estimation. This approach accommodates dynamic load changes and enhances control accuracy.

3) Model Updating and System Identification: Introduce online system identification algorithms to periodically update the load disturbance model, thereby enhancing the system's adaptability to complex load variations.

4.2. Complexity in feedforward parameter design

Designing a feedforward compensator requires a comprehensive understanding of system dynamics. Moreover, parameter tuning involves a trade-off between fast response and system stability, which increases the complexity of controller debugging.

Proposed Solutions:

1) System Modeling and Analysis: At the initial stage of system design, conduct a detailed analysis of the motor's dynamic characteristics through frequency response and time-domain simulations to accurately determine the feedforward compensation gain. Analyzing the system's gain and phase margins can help define the acceptable range of compensation gain.

2) Parameter Optimization Methods: Utilize optimization algorithms (such as genetic algorithms or particle swarm optimization) to automate the tuning of the feedforward compensator gain, ensuring improved response speed while maintaining system stability.

3) Dynamic Gain Adjustment: Instead of using a fixed gain, design the feedforward gain as a dynamic function of the load variation. This approach simplifies tuning complexity and improves adaptability.

4.3. Limitations of hardware platform response

Under high-frequency load variations or fast control requirements, limitations in the sampling frequency and computational capacity of microcontrollers or DSPs may affect the real-time performance and precision of PWM signals, thereby impacting overall control effectiveness.

Proposed Solutions:

1) Enhanced Hardware Performance: Select high-performance microcontrollers (such as high-frequency DSPs or FPGAs [6]) to support higher sampling rates and more accurate control signal generation.

2) Optimized Control Algorithms: Use more efficient digital control algorithms (e.g., discrete-time PID control) to reduce computational delay and improve real-time performance.

3) Offline Computation and Parameter Preprocessing: For computationally intensive tasks, consider preprocessing certain control parameters offline to reduce the burden on the real-time control system.

4) Control Cycle Optimization: Reduce the computational load per control cycle and choose an appropriate time step to avoid instability caused by overly frequent computations.

4.4. Insufficient system robustness

In the presence of unmodeled dynamics or environmental disturbances (such as temperature fluctuations or power supply variations), the effectiveness of feedforward compensation may decline, necessitating the design of robust control strategies to improve system adaptability.

Proposed Solutions:

1) Robust Control Methods: Apply robust control theories, such as $H\infty$ control or sliding mode control, to ensure system stability and performance even in the face of unmodeled dynamics or external disturbances.

2) Environmental Monitoring and Compensation: Adjust control strategies based on real-time monitoring of environmental factors (e.g., temperature or power fluctuations). For instance, motor parameters (such as armature resistance) can be adjusted to compensate for temperature variations, enhancing system adaptability.

3) Fault Detection and Self-Healing Mechanisms: Implement online fault diagnosis and compensation mechanisms. When non-ideal conditions (e.g., sensor errors or environmental changes) are detected, the controller parameters can be automatically adjusted, or a backup control strategy can be activated.

4.5. Discrepancy between simulation and actual results

There may be deviations between ideal simulation outcomes and actual hardware test results due to non-ideal factors such as friction or cogging effects. These require further model refinement and control strategy adjustments during practical implementation.

Proposed Solutions:

1) Practical Hardware Validation: During simulation, gradually incorporate actual hardware parameters (e.g., friction, cogging effects, sensor errors) into the simulation model and conduct hardware-in-the-loop (HIL) testing to bridge the gap between simulation and reality.

2) Physical Modeling and Compensation: Perform detailed physical modeling of hardware components such as motors and drivers, including nonlinear motor effects and mechanical friction or gear effects. Incorporating these compensations into the control strategy reduces discrepancies between simulation and actual performance.

3) Feedback-Based Experimental Adjustment: Use real-time experimental data to iteratively refine the control model. By combining experimental validation with system identification, the model can be periodically updated to better reflect actual application environments.

5. Conclusion

This study addresses the performance degradation issue caused by load disturbances in DC motor speed control systems by proposing and designing a PID control strategy incorporating feedforward compensation. In terms of system modeling, a complete mathematical model of the motor was derived based on electrical and mechanical equations. Through small-signal linearization and Laplace transformation, the system transfer function was obtained, clarifying the mechanism by which load variations affect the dynamic characteristics of rotational speed. In the controller design, a feedforward compensation module was introduced to preemptively correct the control signal using disturbance prediction information, significantly enhancing the system’s ability to suppress the effects of load variations.

For controller implementation, pulse-width modulation (PWM) technology was integrated and executed via a microcontroller or DSP platform, enabling continuous modulation of the input voltage to the DC motor and ensuring both real-time performance and control precision. Simulation and experimental results demonstrate that, compared with conventional PID control, the inclusion of feedforward compensation results in notable improvements across key performance indicators such as overshoot, settling time, and steady-state error. The system, in particular, exhibited superior dynamic response and greater robustness under conditions of abrupt load changes.

Although challenges remain—such as the difficulty of load disturbance modeling, complexity in feedforward parameter design, limitations of hardware response, insufficient system robustness, and discrepancies between simulation and actual results—this study proposes targeted solutions through the adoption of adaptive control, optimization algorithms, robust control strategies, and real hardware validation.

Overall, this research not only deepens the theoretical understanding of load disturbance mechanisms and control strategy optimization but also provides valuable technical reference and practical guidance for the development of high-performance DC motor speed control systems. Future work may further explore online adaptive control based on intelligent optimization algorithms to better accommodate more complex load variations and environmental disturbances.

References

[1] Huang, D., Zhang, X., Peng, J. (2025). Design and simulation of a DC motor speed control system based on PID control. *Hydropower Station Electromechanical Technology*, *48*(1), 12–14. https://doi.org/10.13599/j.cnki.11-5130.2025.01.003

[2] Cui, W., Wang, Y., & Tan, W. (2020). PID control-based approximation to linear active disturbance rejection control. *Control Theory & Applications*, *37*(8), 1781–1789.

[3] Zhu, T. (2023). Design of a DC motor speed control system. *Electronics Production*, *31*(15), 116–119. https://doi.org/10.16589/j.cnki.cn11-3571/tn.2023.15.024

[4] Chi, S. (2023). Research on permanent magnet synchronous motor control system based on feedforward compensation (Master’s thesis). Inner Mongolia University of Science and Technology. https://doi.org/10.27724/d.cnki.gnmgk.2023.000298

[5] Qiu, H. (2016). Research on DC motor speed control system based on STM32 microcontroller. *Electronics World*, (7), 156, 158. https://doi.org/10.19353/j.cnki.dzsj.2016.07.077

[6] Yao, L. (2022). Design of a brushless DC motor speed control system based on Simulink and DSP. *Modern Electronic Technology*, *45*(18), 107–110. https://doi.org/10.16652/j.issn.1004-373x.2022.18.021