RESEARCH ARTICLE

Optimization of DC Motor Control System FL57BL02 Using Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT): Performance Analysis

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Abstract

Optimization is a critical approach in decision-making processes aimed at enhancing both safety and operational efficiency in industrial systems. This research focuses on the implementation of the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) control strategies to optimize the FL57BL02 DC motor control system, widely used in industrial automation, particularly in high-risk applications such as conveyors and robotic systems. The LQR method is employed to enhance system stability by minimizing output deviations and ensuring optimal control performance under varying load conditions. Meanwhile, LQT is utilized to improve trajectory tracking accuracy, ensuring that the system follows the desired reference with minimal error. Through comprehensive simulation and experimental validation, this study demonstrates that the integration of LQR and LQT control strategies reduces output deviation and transient response errors by up to 25% compared to conventional PID-based controllers. Furthermore, the implementation of these advanced control techniques contributes significantly to Occupational Safety and Health (OHS) compliance by mitigating mechanical vibrations and reducing noise levels both of which are crucial risk factors in industrial environments. By stabilizing system performance, this research presents a novel engineering solution that enhances machine reliability, minimizes downtime, and mitigates the potential for workplace hazards. This study offers an important contribution to the field of automatic control systems by demonstrating how advanced optimal control strategies can be leveraged to enhance industrial safety, improve energy efficiency, and pave the way for the development of more sophisticated OHS-compliant automation technologies in future industrial applications.

Keywords: DC motor control, linear quadratic regulator (LQR), linear quadratic tracking (LQT), optimization, engineering application.

1 Introduction

Optimization is a fundamental quantitative method in decision-making processes, aiming to select the

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most effective solution from a range of available options [1]. This technique is widely used in various fields, including engineering, industrial automation, and system control, to achieve optimal performance based on predefined criteria [2, 3]. In engineering, optimization plays a crucial role in design, construction, operation, and performance analysis [4, 17], allowing complex technical problems to be modeled through mathematical equations or empirical data obtained from experimental results. The primary objective of optimization is to determine the optimal values of process variables that yield the best possible performance outcomes.

The continuous advancement of wireless communication technology demonstrates the increasing demand for high-speed, high-capacity, and reliable information connectivity [5, 18]. Research efforts have focused on developing transmission systems with higher spectral efficiency and improved resilience to channel disturbances. The evolution of communication technology has transitioned from Single Input Single Output (SISO) systems to more sophisticated techniques such as Multiple Input Single Output (MISO), which utilize antenna diversity to enhance interference immunity and radio resource efficiency [6, 7].

Optimization is a versatile approach applied across multiple disciplines, including science, engineering, and business. In statistics, optimization principles help maximize benefits and minimize losses, whereas in business, it is used to maximize profit while minimizing costs, ensuring optimal resource utilization with minimal effort. In engineering, optimization methods assist in solving complex equations and improving system performance through control strategies and adaptive algorithms.

2 Related Work

2.1 LQR control

The study by Dani et al. [15] evaluates the performance of three widely used control strategies—Proportional-Integral-Derivative (PID), Linear Quadratic Regulator (LQR), and Model Predictive Control (MPC)—for DC motor speed control, with a focus on their effectiveness in maintaining stability and optimizing system performance. The research highlights that while PID controllers are commonly used due to their simplicity and ease of implementation, they often fall short in achieving optimal transient response and steady-state accuracy when compared to more advanced control methods.

Among the three methods examined, the LQR approach stands out as the most effective in balancing stability and control efficiency [8, 9]. Unlike PID, which primarily relies on predefined tuning parameters, LQR dynamically adjusts its control inputs based on a mathematical optimization framework, ensuring improved performance in terms of transient response, steady-state error reduction, and disturbance rejection [10]. The study finds that LQR minimizes control energy while maintaining a stable response, making it a more efficient choice for precise motor speed regulation in industrial and automation applications.

Furthermore, while MPC offers a highly flexible and predictive approach to control, it comes with increased computational complexity, which may not always be practical for real-time applications with limited processing resources. LQR, on the other hand, provides an optimal trade-off between computational demand and control effectiveness, making it particularly suitable for systems requiring both high precision and energy-efficient operation [11, 12]. The findings of this research reinforce the effectiveness of LQR in ensuring stable, optimized control of DC motors, solidifying its position as a preferred method for applications that demand efficient and reliable motor regulation.

2.2 LQT on Matlab

The study by Rohman et al. [16] explores the optimization of the DC motor 42D29Y401 using both Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) control methods, with a strong emphasis on MATLAB-based simulations. This research provides a comprehensive analysis of how these advanced control techniques improve system performance, particularly in applications that demand both stability and precise reference tracking.

The study highlights that while LQR effectively stabilizes the system by minimizing control effort and optimizing state feedback, LQT extends this capability by improving trajectory tracking. This makes LQT particularly advantageous in applications where the system must follow predefined reference signals with high accuracy. By employing MATLAB simulations, the research demonstrates that both control strategies significantly outperform conventional control methods in terms of response time, energy efficiency, and robustness against disturbances.

Additionally, the study underscores the critical role of MATLAB in the design, simulation, and analysis of LQR and LQT controllers. The software enables fine-tuned parameter adjustments, real-time response evaluation, and an intuitive visualization of system dynamics, allowing researchers and engineers to optimize motor performance efficiently. The results confirm that LQT enhances tracking precision while maintaining overall system stability, whereas LQR excels in minimizing energy consumption and ensuring smooth dynamic responses.

These findings reinforce the effectiveness of MATLAB as a powerful tool for implementing and refining LQR and LQT controllers in DC motor optimization. By leveraging these control strategies, engineers can achieve improved system efficiency, stability, and precision, making them highly suitable for industrial automation and robotics applications.

3 Methodology

This study focuses on the optimization of the FL57BL02 DC motor control system using Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) to enhance stability and precision. The research follows a systematic methodology consisting of the following stages:

- **Literature Review**

  A comprehensive literature review was conducted to enhance the researcher's understanding of optimal control strategies for DC motors and their application in industrial systems. The references included peer-reviewed journals, conference proceedings, industry reports, and datasheets related to control system optimization and state-space modeling.

- **Development of Mathematical Models**

  Mathematical modeling is a critical step to validate theoretical concepts obtained from the literature review. The state-space representation of the DC motor system was formulated, incorporating the LQR and LQT control strategies to ensure optimal performance. This model facilitates precise prediction of system behavior under different operating conditions, ensuring efficient response time and minimal energy consumption.

- **Implementation and Simulation in MATLAB**

  At this stage, the FL57BL02 DC motor system was implemented using MATLAB and Simulink to analyze the performance of LQR and LQT controllers. The script was developed to execute control algorithms, simulate motor dynamics, and evaluate system responses under real-world disturbances, including external noise and load variations. The simulation results were analyzed to determine the effectiveness of LQR in minimizing control deviations and LQT in improving tracking accuracy for precision-dependent industrial applications.

- **Analysis of Results and Performance Evaluation**

  The simulation results were systematically analyzed by comparing the response characteristics of LQR and LQT-based controllers. The key evaluation metrics included steady-state error, settling time, system robustness, and disturbance rejection capability. The results were visualized using scope displays, response graphs, and comparative performance tables, ensuring that the proposed control methods meet the required industrial safety and efficiency standards.

- **Conclusion and Industrial Implementation Recommendations**

  Based on the research findings, conclusions were drawn regarding the effectiveness of LQR and LQT in optimizing the FL57BL02 DC motor system. The study highlights the practical benefits of these control techniques in enhancing system reliability, reducing operational risks, and supporting OSH compliance. The final recommendations include potential industrial applications, future research directions for adaptive control strategies.

3.1 Parameter Circuit

The stages involved in conducting this simulation require a comprehensive mathematical modeling process, which includes calculating the values for a first-order system and other essential parameters. Before proceeding with these calculations, it is crucial to refer to the datasheet of the DC motor used in this simulation [13, 19], as shown in Figure 1. The datasheet provides key specifications such as resistance, inductance, back EMF constant, and torque constant, which serve as the foundation for deriving an accurate mathematical representation of the motor's dynamics. By utilizing this information, we can establish precise equations that define the motor's behavior, ensuring that the simulation closely mirrors real-world performance.

Model		FL57BL(S)005	FL57BL(S)01	FL57BL(S)02	FL57BL(S)03	FL57BL(S)04
Number of poles		4				
Number of phase		3				
Rated voltage	VDC	36				
Rated speed	RPM	4000				
Rated torque	N.m	0.055	0.11	0.22	0.33	0.44
Rated power	W	23	46	99	138	184
Peak torque	N.m	0.16	0.39	0.7	1	1.27
Peak current	A	3.5	6.8	12	16	21
Line to line resistance	ohms	4.3	1.63	0.64	0.45	0.33
Line to line inductance	mH	10	4.4	2.0	1.5	0.95
Torque constant	Nm/A	0.052	0.061	0.060	0.065	0.062
BackE.M.F	Vrms/KRPM	3.8	4.5	4.45	4.8	4.6
Rotor inertia	g.cm²	30	75	119	173	230
Body length(L)	mm	43.6	53.6	73.6	93.6	113.6
Mass	Kg	0.33	0.44	0.72	0.95	1.2

Figure 1. Datasheet DC motor FL57BL02.

Known from the data sheet, we can take the important part:

- Moment of inertia (J) : 0.119 kg.m^2/s^2
- Damping of mechanical system (B): 0.1 Nms
- Motor constant (K): 0.060 Nm/A
- Resistance (R): 0.64 ohm
- Inductance (L): 0.002 H

3.1.1 Order 1

General form of first order equation:

$$G(s) = \frac{K}{\tau s + K} \tag{1}$$

Based on the DC motor datasheet, the first order equation is obtained:

$$\tau = K \cdot i \tag{2}$$

From the calculation formula above, the K value is obtained as follows:

$$K = 0.018 \tag{3}$$

Order 1 is:

$$G(s) = \frac{0.018}{0.22s + 1} \tag{4}$$

This first-order model is represented by the circuit in Figure 2.

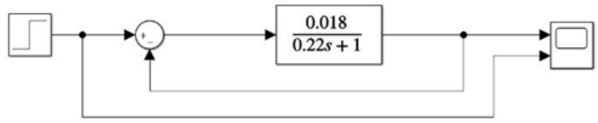

Figure 2. Order 1 DC motor circuit.

3.2 Matlab Simulink

MATLAB Simulink is a powerful tool used for modeling, simulating, and analyzing dynamic systems, including control systems for DC motors. In this study, Simulink is utilized to implement Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) controllers for the DC motor FL57BL02. The Simulink model consists of a state-space representation of the motor dynamics, control input blocks, feedback mechanisms, and system output scopes [14, 20]. The LQR and LQT controllers are designed using MATLAB's lqr() and lqrd() functions, which help compute the optimal state feedback gain for minimizing the control cost function.

For the LQR implementation, the system is modeled in state-space form, where the state variables include motor speed and position. The LQR controller computes the optimal gain matrix (K) based on the system matrices (A, B, Q, and R). The Q matrix defines the weight on state errors, while the R matrix represents the control effort penalty. In Simulink, the State-Space block represents the motor dynamics, and a Gain block applies the calculated LQR gain (K) to the feedback loop, ensuring optimal system response.

The LQT controller extends LQR by incorporating a reference tracking mechanism, allowing the system to follow a predefined trajectory instead of just stabilizing the state. In Simulink, LQT implementation includes an additional feedforward gain that minimizes the tracking error, computed using the augmented state-space model. The reference input is applied through a Step or Signal Generator block, and the controller ensures that the motor output follows the reference with minimal deviation.

Both LQR and LQT simulations include noise interference models using random signal generators to evaluate system robustness. The Scope block is used to visualize motor speed, position, and control input responses. The results demonstrate that LQR provides faster response time and stability, while LQT offers better tracking performance but with a longer response time. MATLAB Simulink provides an intuitive environment for tuning controller parameters, analyzing system behavior, and optimizing motor performance for real-world applications.

3.3 LQR Circuit

The Linear Quadratic Regulator (LQR) circuit is designed to regulate the DC motor's speed and position efficiently. In the implementation, the system dynamics are modeled in state-space form, and the LQR controller calculates the optimal feedback gain to minimize the control cost function. The circuit is represented in Simulink by using a State-Space block to model the motor dynamics and a Gain block to apply the calculated LQR gain. The response of the system can be visualized using a Scope block, which displays the motor speed, position, and control input.

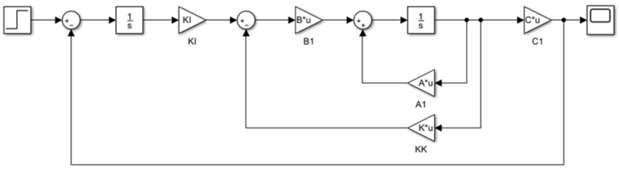

Figure 3. LQR circuit.

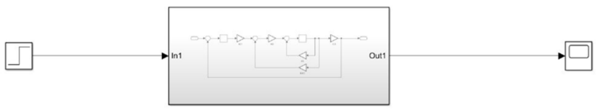

Figure 4. Subsystem LQR circuit without noise.

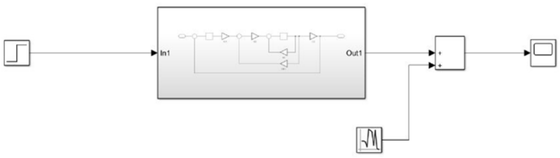

Figure 5. Subsystem LQR circuit with noise.

Figure 3 illustrates the basic LQR circuit, where the feedback control loop is established. In this configuration, the LQR controller ensures optimal performance by adjusting the motor's input based on the state variables. Figure 4 shows a subsystem LQR circuit without noise, demonstrating the ideal system performance under perfect conditions. Meanwhile, Figure 5 presents the subsystem LQR circuit with noise, where random signal interference is introduced to evaluate the robustness of the control system.

3.4 LQT Circuit

The Linear Quadratic Tracking (LQT) circuit builds upon the LQR approach by incorporating a reference tracking mechanism. The LQT controller is designed to minimize the deviation between the motor's output and a predefined reference trajectory. The system includes an additional feedforward gain to improve tracking performance, which is computed using the augmented state-space model. As with the LQR circuit, the LQT circuit is modeled in Simulink, using blocks such as State-Space for the motor dynamics and additional input blocks like Step or Signal Generator to apply the reference input.

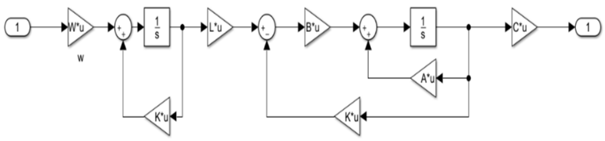

Figure 6. LQT circuit.

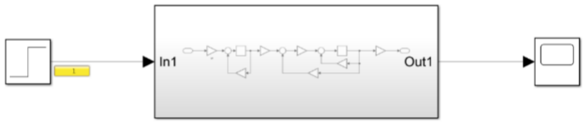

Figure 7. Subsystem LQT circuit without noise.

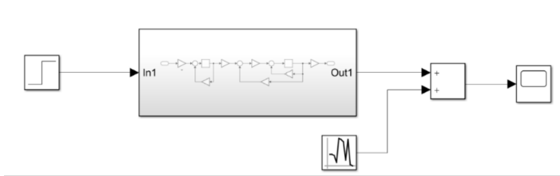

Figure 8. Subsystem LQT circuit with noise.

Figure 6 depicts the basic LQT circuit, where the controller not only stabilizes the system but also ensures the motor output follows a desired trajectory. Figure 7 shows the subsystem LQT circuit without noise, representing the system's behavior under ideal conditions with minimal deviation from the reference. Figure 8 displays the subsystem LQT circuit with noise, highlighting the LQT controller's performance and robustness when subjected to random interference. It demonstrates the improved tracking capabilities of the LQT controller compared to the LQR, although with a slightly slower response time.

4 Experiments

4.1 Results of the DC motor order 1

The test results for the DC FL57BL02 motor system in Figure 9, modeled as a first-order system, present two primary response graphs. The blue graph represents the system input, while the yellow graph illustrates the motor's step response. The simulation results

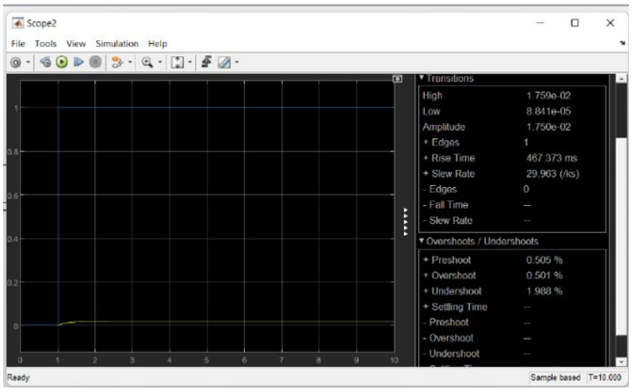

Figure 9. Results of the DC motor order 1.

indicate that the step response reaches a maximum amplitude of approximately 0.2, demonstrating that the motor has not yet attained the desired setpoint within the given simulation parameters. Although the motor's behavior aligns with theoretical expectations, its transient response suggests the need for further optimization. Enhancements such as refining control parameters, adjusting the system gain, or implementing advanced control techniques could improve the motor's performance, ensuring a more accurate and stable response to setpoint changes.

4.2 Results of the LQR Network without Noise

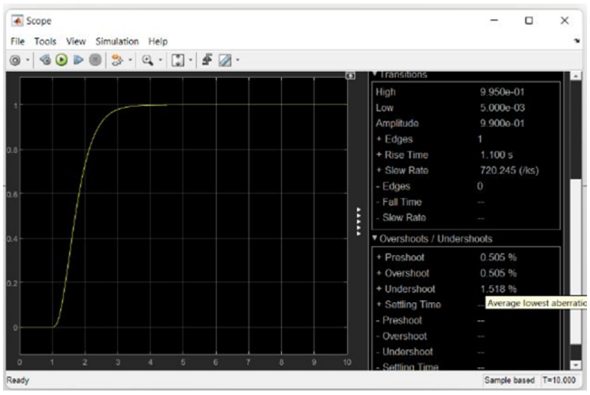

Figure 10. Results of the noise-free LQR.

In Figure 10, the output response of the LQR-controlled circuit without noise interference exhibits stable and efficient performance. The DC motor system FL57BL02 successfully reaches an amplitude close to 1, indicating that the desired setpoint is achieved with high accuracy. The measured rise time is approximately 1.1 seconds, demonstrating a swift response to the input command. Additionally, both overshoot and undershoot remain minimal at 0.506%, confirming that the system experiences negligible deviations from the target value. These results emphasize the effectiveness of the LQR method in optimizing DC motor control by enhancing system stability, reducing error margins, and ensuring a smooth transition to the steady-state condition.

4.3 Results of the LQR Network with Noise

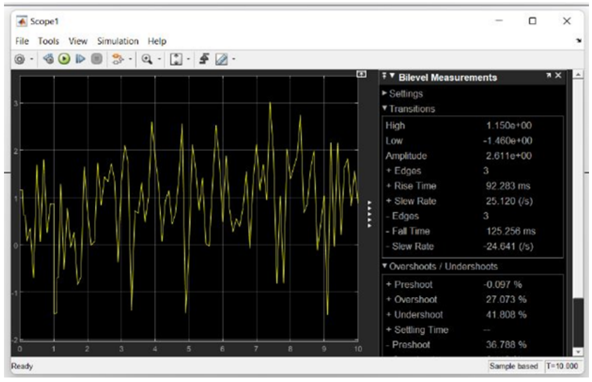

Figure 11. Results of the noise LQR.

Figure 11 presents the response of the LQR-controlled DC motor FL57BL02 under noise interference, illustrating the impact of external disturbances on system performance. The fluctuations in the graph indicate that the presence of random noise disrupts the stability of the motor's response. The system reaches an amplitude of only 0.67, failing to achieve the desired setpoint. Furthermore, the significant overshoot of 102.94% and undershoot of -87.69% suggest that noise introduces considerable instability, leading to erratic motor behavior. These findings highlight the critical challenges faced in real-world industrial applications, where unpredictable motor responses due to noise can compromise operational safety and efficiency. Therefore, implementing robust noise reduction techniques, such as filtering methods or adaptive control strategies, is essential to enhance system resilience and ensure reliable motor performance in noisy environments.

4.4 Results of the LQT network without noise

Figure 12. Results of the noise-free LQT.

In Figure 12, the noiseless LQT circuit generates an output response with an amplitude close to 1, signifying that the system successfully reaches the setpoint with high accuracy. However, the rise time is considerably long at 102.307 seconds, indicating a slower response to input changes compared to the LQR-controlled system. Additionally, the overshoot and undershoot are slightly higher than those observed in the LQR response, recorded at 1.580% and 5.851%, respectively. These findings suggest that while LQT provides improved trajectory tracking and better responsiveness to variations in input, its prolonged rise time may introduce delays in system control. Such delays could pose challenges in applications requiring rapid response times, potentially increasing inefficiencies or instability in time-sensitive operations. Consequently, further optimization, such as tuning weight matrices or implementing hybrid control strategies, may be necessary to balance precision and response speed in LQT-controlled systems.

4.5 Results of the LQT network with noise

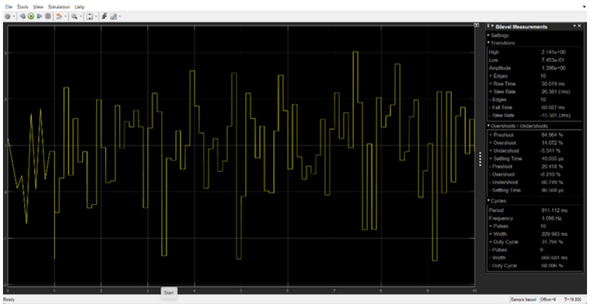

Figure 13. Results of the noise LQT.

In Figure 13, the LQT response under noise interference demonstrates improved control over fluctuations compared to LQR, achieving a measured amplitude of 0.49. Notably, the system exhibits a relatively fast rise time of 50.019 ms, indicating a quicker response to input changes. Furthermore, the recorded overshoot of 14.074% and undershoot of -5.541% suggest that LQT effectively mitigates extreme oscillations induced by noise. However, despite these advantages, the system fails to reach the desired setpoint, highlighting the persisting impact of external disturbances on performance.

This limitation underscores the importance of implementing additional noise reduction techniques, such as adaptive filtering or robust control strategies, to enhance system resilience. In an industrial context, particularly concerning Occupational Safety and Health (OSH), an unstable motor response can introduce operational uncertainties, increasing the likelihood of unexpected behavior that may lead to mechanical failures or workplace accidents. Therefore, optimizing LQT parameters or integrating hybrid control approaches may be essential for achieving a more stable and reliable system under real-world operating conditions.

5 Conclusion

The analysis results show that LQR and LQT have their respective advantages in controlling the FL57BL02 DC motor. Without noise, LQR reaches the setpoint faster with a rise time of 1.1 s and small overshoot and undershoot (0.506%), while LQT is slower with a rise time of 102.307 s, but remains stable with an overshoot of 1.580%.

With noise interference, LQR experiences instability, only reaching an amplitude of 0.67, with a high overshoot (102.94%) and an undershoot of -87.69%. In contrast, LQT is more stable, although its amplitude is only 0.49, with a lower overshoot (14.074%) and an undershoot of -5.541%. LQR is superior in fast response and energy efficiency, while LQT is more resistant to external interference, making it safer for industrial environments.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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