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Optimization of DC Motor 054b-2 Using LQR and LQT Methods in MATLAB

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Abstract

The system model is crucial for the design of control systems, as it serves as a reference for developing control strategies. An accurate system model is necessary to ensure effective performance. This experiment focuses on designing an online system identification technique based on MATLAB to obtain models for Single Input, Single Output (SISO), Multi Input, Single Output (MISO), and Multi Input, Multi Output (MIMO) systems. The system models were simulated using the 054B-2 DC Motor model for both Order 1 and Order 2 configurations. In control systems, noise is often present, acting as a disturbance that affects the system's output. Noise can cause undesirable effects such as high overshoot, impacting system performance. Therefore, noise was introduced into the SISO, SIMO, MISO, and MIMO systems to observe its impact. The online system identification process was carried out using Simulink, a MATLAB-based tool for modeling and simulation. To optimize control performance, the experiment utilized the Linear Quadratic Regulator (LQR), a widely used optimal control method in fields like industry, robotics, and engineering. The advantage of LQR lies in its ability to provide optimal solutions for system control problems by using the state-space approach. Additionally, the Linear Quadratic Tracking (LQT) method was implemented as an alternative to LQR. LQT is a linear control system that tracks the path specified by the input, ensuring that the output follows a desired trajectory. The results of the experiment demonstrate the effectiveness of these control strategies in handling various system models with noise disturbances.

Keywords: control, simulink, DC motor, LQR, LQT.

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1 Introduction

Control system optimization aims to develop a system with optimal performance that adheres to both physical constraints and design requirements [1]. By employing a performance index-based optimization approach, deviations from an ideal system condition can be minimized, ensuring improved efficiency and stability. Among various control methods, the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) provide a robust framework for state-based system control. These techniques enable precise regulation of system behavior, ensuring

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that performance remains optimal within predefined constraints [2].

DC motors are widely used in industrial applications, robotics, and electrical experiments due to their efficiency, speed stability, and ease of control [3, 4]. These motors function based on the interaction between the magnetic fields of the rotor and stator, generating rotational motion. One of the main advantages of DC motors is their ability to deliver smooth and stable speed regulation, making them highly compatible with modern control systems. Their straightforward integration with various control strategies further enhances their appeal for research and industrial applications. However, like all electromechanical devices, DC motors require periodic maintenance to sustain optimal performance, particularly in components prone to wear and tear [4, 5].

The foundation of effective control system design lies in developing accurate mathematical models. Two primary approaches for model development involve MATLAB-based observational data analysis and simulation techniques. In this study, simulations are conducted using the DC motor type 054B-2, representing both first-order and second-order system dynamics. The first-order system accounts for a single dominant variable influencing the system's response, while the second-order model incorporates multiple interacting factors for a more comprehensive representation [6]. These simulations serve as a critical step in evaluating system behavior before implementation in real-world applications, reducing potential risks and operational costs.

The LQR method is designed to optimize linear systems by minimizing the quadratic integral of error, thereby ensuring optimal state feedback with constant gains. This technique has been widely applied across various engineering disciplines, including industrial automation and robotics, due to its ability to enhance system stability and efficiency. On the other hand, the LQT method extends this concept by improving the system's ability to accurately track reference inputs, making it particularly suitable for applications requiring dynamic response and adaptability [7, 8]. The ability of LQT to accommodate changing control inputs makes it a preferred choice for systems that must operate under varying conditions [9, 10].

In this research, the DC motor type 054B-2 is utilized to implement and compare the performance of LQR and LQT methods using MATLAB and Simulink. By referencing motor datasheet parameters, the study aims to assess how these optimization techniques contribute to enhancing control system stability and accuracy. Through this approach, the research provides valuable insights into advanced control methodologies, contributing to the development of more efficient industrial applications and modern control systems.

2 Related Work

The next section will present previous studies that are related to the current topic. Below are summaries of these studies.

2.1 Design and Simulation of DC Motor Control Based on LQR and LQT

Satrianata (2024) explores the design and simulation of DC motor control systems using Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) with the goal of achieving optimal control [2]. The study discusses the design principles of both controllers and their application to DC motor systems for improved performance and stability.

The LQR design in this research focuses on determining the optimal feedback gain matrix to minimize a quadratic cost function based on system errors (e.g., position and speed) and control efforts. The design procedure includes setting up the state-space model of the DC motor, defining the weighting matrices, and calculating the optimal feedback gain using MATLAB tools [1].

In contrast, the LQT design is extended to incorporate tracking capabilities, aiming not only to stabilize the system but also to follow a reference trajectory. The LQT controller involves a similar design process as LQR but adds additional terms in the cost function to account for tracking errors, allowing the system to follow a specific reference while maintaining optimal control performance.

Both controllers are simulated in MATLAB Simulink, where the system's state-space representation and control law are implemented. The simulation results show that LQR effectively stabilizes the DC motor with minimal control effort, while LQT provides better tracking performance, making it ideal for systems that require precise reference following [1, 3].

The comparison of LQR and LQT highlights the strengths of each method. LQR is effective in providing robust stability and fast response, making it suitable for systems needing quick stabilization, while LQT excels in tracking scenarios, offering precise reference following without compromising stability.

Overall, the study underscores the importance of designing LQR and LQT controllers tailored to the specific needs of DC motor control systems, ensuring optimal performance and efficiency under various operational conditions.

2.2 Linear Quadratic Regulator (LQR) in DC Motor Systems

A study by Firdaus (2024) compares two commonly used control methods in DC motor systems: the Linear Quadratic Regulator (LQR) and the Proportional-Integral-Derivative (PID) Controllers. The primary goal of this research is to enhance the stability of the DC motor system by comparing the performance of both methods [1].

In this study, LQR is applied to achieve optimal control, minimizing the cost function that encompasses position and speed errors, as well as system input control. LQR works by calculating a feedback matrix that adjusts the control input based on the system's state, including motor position and speed. LQR offers a more precise and stable system, especially in the presence of disturbances or model uncertainty.

The study shows that LQR provides faster and more stable responses than PID in DC motor systems, especially when load variations occur. Compared to PID, LQR delivers a more efficient solution for optimizing motor performance, as PID tends to be more sensitive to parameter changes and tuning errors [11].

Overall, the research concludes that LQR provides superior stability and more structured programming for optimal control under complex conditions compared to PID.

2.3 Control Methods for Optimization of DC Motor Control Systems Based on MATLAB Simulink

Syaifudin (2024) explores the use of Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) control methods for optimizing DC motor control systems, with the goal of improving energy efficiency for small-scale industries, leveraging MATLAB Simulink for simulation [2].

In this study, MATLAB Simulink is used as the platform for simulating both LQR and LQT controllers. The simulation assesses the performance and efficiency of these control methods in the context of the DC motor system. MATLAB Simulink provides a comprehensive environment for modeling the DC motor dynamics and testing the control strategies.

The research demonstrates how the LQR controller is implemented in MATLAB Simulink to optimize energy usage while maintaining system stability and performance. The results show that LQR is effective in minimizing the cost function related to energy consumption, motor speed, and position regulation [12, 13].

Additionally, the study compares LQR with LQT, showing that both methods offer improvements in energy efficiency and system performance, with LQR being more stable and faster, particularly under varying load conditions.

The study emphasizes the value of MATLAB Simulink in simulating and optimizing DC motor control systems, particularly for enhancing energy efficiency in small industries.

3 Methodology

This chapter describes the methodology used in this study. The research phases are explained in the next subsection.

3.1 Research stages

In this study, the first step involves selecting a research object, which is the DC motor type 054B-2. This motor is chosen based on its technical specifications, which are deemed suitable for the experimental requirements. The DC 054B-2 motor datasheet from the PITMAN DC Motors series serves as the primary reference to ensure accuracy in data collection and model validation.

The subsequent stage involves performing mathematical calculations based on the determined technical specifications of the motor [14]. Two computational approaches, specifically first-order and second-order models, are applied in this study to generate a mathematical model that closely matches the dynamic characteristics of the DC 054B-2 motor.

The order 1 method aims to find the transfer function based on Equation (1):

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

Where K is the constant calculated using Equation (2):

$$K = \frac{\tau}{I} \tag{2}$$

Using τ as the torque (in Nm) and I as the current (in A), the datasheet provides a torque value of 0.052 Nm and a current of 1.7 A. These values are used to calculate the motor constant (K). The constant K is determined by dividing the torque (τ) by the current (I)

This constant K is then substituted into Equation (1) to obtain the first-order transfer function of the motor [15, 16]. The first-order transfer function represents the relationship between the input (current) and the output (torque or speed), taking into account the dynamic behavior of the motor [17]. The 2nd order approach uses Equation (3):

$$G(s) = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{3}$$

In this equation, ζ is the attenuation ratio, and ω_n is the angular velocity calculated using Equation (4):

$$\omega_n = 2\pi f \tag{4}$$

The frequency (f) is obtained from the specifications of the DC motor. Using this value, the angular velocity (ω_n) and damping ratio (ζ) are calculated, and these results are then used to derive the second-order transfer function [18].

3.2 MATLAB Simulink

Once the mathematical model is developed, the next phase of the research involves conducting simulations using MATLAB Simulink. This phase is critical for validating the theoretical model and assessing the practical feasibility of the proposed control strategies. To achieve this, the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT) models are implemented within Simulink to evaluate the performance of DC motor control systems under different operating conditions [19]. These simulations allow researchers to analyze how effectively each control method regulates the motor's speed and position while minimizing control effort.

To ensure a comprehensive evaluation, simulations are conducted both in ideal conditions and in the presence of external disturbances and measurement noise. The inclusion of noise in the simulation environment helps assess the robustness of the control system, determining its ability to maintain stability and accuracy despite real-world uncertainties. By subjecting the system to noise, researchers can analyze how well the controllers mitigate disruptions and maintain desired performance levels.

The simulation results are systematically analyzed by comparing the performance of the LQR and LQT control methods [19]. Key optimization parameters, such as system stability, response time, overshoot, and disturbance attenuation, are carefully evaluated using a structured approach tailored to the specific requirements of the control system. Stability is assessed to ensure that the system remains within acceptable operational limits under varying conditions, while response time is analyzed to determine how quickly the motor reacts to changes in input. Additionally, attenuation of disturbances is examined to quantify the effectiveness of each control method in suppressing unwanted fluctuations and maintaining consistent output.

By leveraging MATLAB Simulink for detailed simulation studies, the research aims to identify the most effective control strategy for optimizing DC motor performance. The insights gained from these simulations provide valuable guidance for refining control algorithms, enhancing system efficiency, and ensuring reliable operation in practical applications.

3.3 Modelling and Components Used

The mathematical model derived from the first- and second-order transfer functions is implemented using a MATLAB script, which incorporates key system parameters essential for accurate modeling and control optimization. These parameters include the moment of inertia (J), which defines the system's resistance to angular acceleration; the damping ratio (b), which accounts for energy dissipation due to friction; the torque constant (K), which relates current input to the generated torque; the resistance (R) of the electrical circuit; and the inductance (L), which influences the system's dynamic response.

This MATLAB script plays a crucial role in analyzing and optimizing the system's performance through advanced control techniques, specifically Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT) optimization methods. LQR is widely used in control engineering to determine optimal state-feedback gains by minimizing a cost function that balances control effort and system performance. Meanwhile, LQT extends this approach by optimizing tracking performance for reference inputs. By implementing these control strategies, the script enhances system stability, reduces steady-state error, and improves dynamic response.

Below is a section of the MATLAB script used for LQR and LQT optimization, illustrating how the mathematical model is structured and integrated within the control framework:

```
% Program LQR
Clear;
CLC;
J = 0.000016;
b = 0.0000963;
K = 0.03;
R = 1.09;
L = 0.016;
A = [-b/J K/J; -K/L -R/L];
B = [0; 1/L];
C = [1 0];
Q = [1 0 0; 0 1 0; 0 0 1000];
R = [1];
K_lqr = lqr(A, B, Q, R);
disp(K_lqr);

% Program LQT
Clear;
CLC;
J = 0.000016;
b = 0.000011;
K = 0.03;
R = 1.03;
L = 0.0016;
A = [-b/J K/J; -K/L -R/L];
B = [0; 1/L];
C = [1 0];
Q = 10;
R = 0.0000001;
K_lqt = lqr(A, B, Q, R);
disp(K_lqt);
```

The system simulation was conducted under various scenarios, including the impact of noise on the plant, to assess the control performance. The simulation utilized MATLAB Simulink components, incorporating LQR and LQT subsystems both with and without noise interference.

4 Experiments

This study provides a comprehensive simulation analysis of the performance of the DC 054B-2 motor using the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT) approaches. The following is a detailed overview of the simulation results, demonstrating the effectiveness of both methods under normal conditions (without noise) and in the presence of noise.

4.1 LQR Result Simulation

4.1.1 LQR Simulation Result without Noise

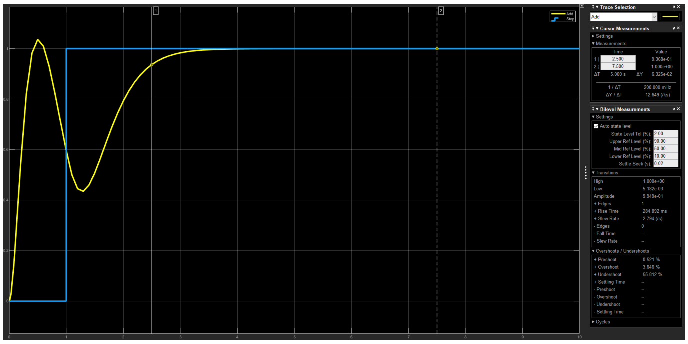

Figure 1. LQR response step display without noise.

In the simulation without noise interference, Figure 1 presents the step response graph of the DC 054B-2 motor. The blue curve represents the set point with a value of 1, while the yellow curve illustrates the system's response. The simulation results indicate the following:

Maximum amplitude: 0.994

Stabilization time: 4 seconds

Overshoot: 3.646%

Undershoot: 55.821%

These findings suggest that the system reaches stability with an amplitude close to the set point. However, the high undershoot value indicates that the initial response is not yet optimal.

4.1.2 LQR Simulation Result with Noise

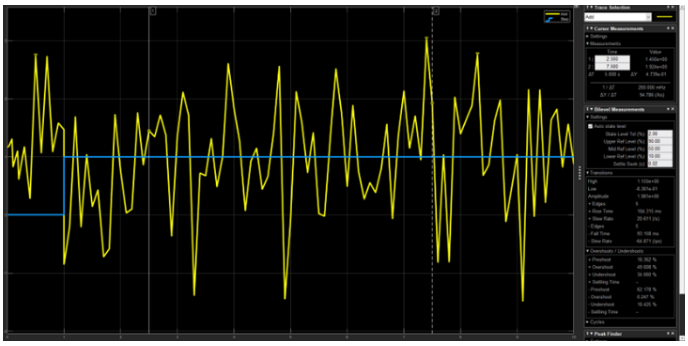

Figure 2. LQR step response display (with noise).

Figure 2 presents the simulation results when noise is introduced into the system. The key performance metrics are as follows:

Maximum amplitude: 1.98

Overshoot: 49%

Undershoot: 34%

Compared to the noise-free scenario, the presence of noise significantly impacts system stability, leading to a substantial increase in both overshoot and undershoot.

4.2 LQT Result Simulation

4.2.1 LQT Simulation Result without Noise

Figure 3. LQT step response display without noise.

Under normal conditions without noise, Figure 3 illustrates the system's response using the LQT method, with the following key parameters:

Maximum amplitude: 0.995

Rise time: 4,766 μs

Overshoot: 5.851%

Undershoot: 0.625%

The simulation results indicate stable performance with relatively low overshoot and undershoot values, demonstrating the effectiveness of the LQT method in minimizing disturbances and enhancing system response.

4.2.2 LQT Simulation Result with Noise

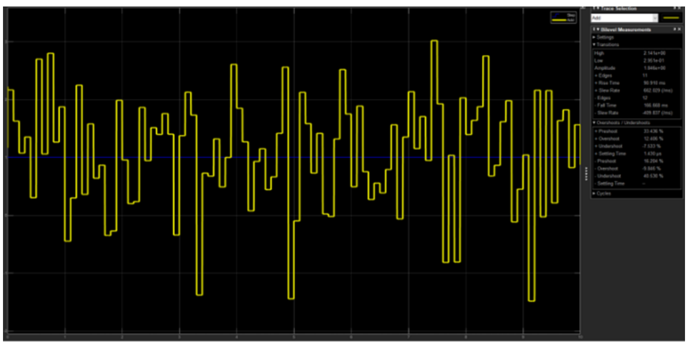

Figure 4. LQT step response display using noise.

With the addition of noise, Figure 4 presents the simulation results as follows:

Maximum amplitude: 1.846

Rise time: 90.91 ms

Overshoot: 12.406%

Undershoot: -7.533%

These results indicate that noise impacts the system's stability; however, the response amplitude remains close to the set point.

4.3 Comparison Simulation Result

Table 1. Comparison of normal conditions and noise based.

System	Usual	Noise
LQR	The amplitude value was 0.994 with overshoot and undershoot values of 3.646% and 55.821%, respectively.	The amplitude value was 1.98 with overshoot and undershoot values of 49% and 34%, respectively.
LQT	The result of the amplitude value was 0.995 with a rise time of 4.766μs. The overshoot and undershoot in this simulation resulted in 5.581% and 0.625%.	The result of the amplitude value was 1.846 with a rise time of 90.91ms. The overshoot and undershoot in this simulation resulted in 12.406% and -7.533%.

As shown in Table 1, under usual conditions, the LQR control method produced an amplitude value of 0.994, with an overshoot of 3.646% and an undershoot of 55.821%. However, when noise was introduced, the amplitude value increased to 1.98, with significantly higher overshoot and undershoot values of 49% and 34%, respectively. Similarly, the LQT control method under normal conditions resulted in an amplitude value of 0.995, with a rise time of 4.766 μs, and overshoot and undershoot values of 5.581% and 0.625%, respectively. When subjected to noise, the amplitude value rose to 1.846, with a rise time of 90.91 ms, while the overshoot and undershoot increased to 12.406% and -7.533%, respectively. These results indicate that both control methods perform effectively under ideal conditions but experience varying degrees of sensitivity to noise, with LQR showing a more pronounced impact in terms of overshoot and undershoot deviations.

5 Conclusion

Based on the simulation results, the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker

(LQT) methods exhibit distinct characteristics and performance in controlling the DC 054B-2 motor. The LQR method provides a stable response with an amplitude close to the set point; however, it has a notable drawback in the form of significant undershoot, particularly in the absence of noise. When noise is introduced, the LQR method experiences a considerable increase in overshoot and undershoot, leading to reduced system stability.

In contrast, the LQT method demonstrates superior performance with faster response times and more stable response graphs, regardless of noise conditions. Although noise affects amplitude stability, the LQT method maintains lower overshoot and undershoot values compared to the LQR method. Overall, LQT proves to be more effective in ensuring system stability and mitigating disturbances, making it a more suitable choice for DC motor control applications.

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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