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Evaluation of the Application of LQR and LQT Methods for DC Motor Control in Improving Energy Efficiency in the Maritime Community Electrical System with MATLAB Simulink Application

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Abstract: *This study aims to investigate the wave characteristics generated by the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) control systems, implemented on a PitmanExpress™ DC motor model 14207S007. The research methodology is based on simulations, starting with the acquisition of the mathematical model data of the DC motor in the form of a transfer function. The second set of data required includes the motor's state-space values, which are then converted into variables for MATLAB programming. These two sets of data are integrated into a unified system consisting of LQR or LQT subsystems, with first-order or second-order configurations, within the MATLAB SIMULINK application. Following data acquisition from the simulation scope results, the system is subjected to noise disturbances to assess the robustness of the control systems. This paper focuses on evaluating the effectiveness of LQR and LQT methods when applied to DC motors, particularly in the context of improving energy efficiency in community-driven projects, such as those in maritime communities. These methods are expected to contribute to energy sustainability and cost reduction in local energy management systems, supporting the development of sustainable energy solutions in rural and coastal areas. The findings from this study are aimed at community empowerment by introducing innovative, energy-efficient solutions that can be adopted by maritime communities to reduce dependency on non-renewable energy sources, ultimately improving the economic stability of such communities.*

Keywords: *DC Motor, LQR, LQT, MATLAB, SIMULINK, Control Systems, Community Empowerment, Energy Efficiency, Maritime Communities.*

Introduction

In today's rapidly growing world, the increasing demand for communication over long distances requires the enhancement of data transmission through wireless media to meet the need for fast and accurate communication (Johnson, 2020). To meet these requirements, performance, transfer speed, and quality must be continually improved. Parameters such as power and data transmission depend primarily on the transmitter used for sending and receiving signals, as well as on the external interference that arises in the system in the form of noise (Smith & White, 2019).

This article presents both theoretical and practical analysis of the application of Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT) control systems on a DC motor, simulated using MATLAB SIMULINK, to study the impact of different control systems on the output generated and their behavior when affected by noise (Lee & Cho, 2018). The LQR method is one of the optimal control techniques used in space-based systems (Kumar & Lee, 2020). LQR controllers involve two key parameters:

the weighting matrices Q and R, which must be determined to achieve the desired optimal control function. The Linear Quadratic Optimization technique moves the system's state from an initial state x(t0) to a final state x(t), determining the input signal that minimizes the squared performance index. The cost function of this problem is the squared integral over time of the state vector x and the input vector u, as shown in the equation:

$$X^T QX + U^T RU \quad (1)$$

where Q is a positive semidefinite matrix and R is a positive definite matrix (Zhang & Wang, 2022). Based on the above, variations in the parameters of the linear-quadratic design problem can be determined for termination conditions, which can influence the cost function (Baker & Fox, 2021). Practical implementations of LQR include speed control of squirrel-cage motors, generator frequency control, and quadcopter drones (Shrestha & Dhakal, 2023). The importance of LQR lies in its ability to combine system optimization with discipline to achieve the desired point while minimizing errors, thus aligning the system's behavior with expectations.

Linear Quadratic Tracking (LQT) is an optimal control method applied to linear systems with quadratic criteria to solve tracking problems (Kumar & Lee, 2020). The general form of the state equations is as follows:

$$x = Ax + Bu \quad (2)$$

$$y = Cx \quad (3)$$

By minimizing the energy (cost function/quadratic function) through the performance index in the interval [t0, ∞], the following equation holds:

$$J = \frac{1}{2}\int_0^\infty e^T Q + u^T Ru ¿ dt ¿ \quad (4)$$

As the value of Q increases, the solution approaches the minimum point, while increasing the value of R results in lower energy usage (Zhang & Wang, 2022). Figure 1 shows the block diagram of the optimal control system. The goal is for the solution to the Riccati equation to yield a matrix with small values, as follows:

$$K = R^{-1} B^T P \quad (5)$$

$$u = -Kx \quad (6)$$

In the system optimization course, the application of LQR and LQT methods is discussed for DC motor systems, with accompanying data sheets (Johnson, 2020). The data is entered into MATLAB programming and then simulated using MATLAB Simulink to observe the system's step response (Smith & White, 2019). The DC motor used is a BN-42 model, equipped with inertia moment values, motor constants, depletion degree, resistance, and inductance (Baker & Fox, 2021).

Methodology

1. Research Stages

The initial stage of the research involves a thorough preparation process, including familiarization with the research object, creation of the mathematical model, state-space programming, and the design of the circuit on MATLAB. The object of research, the DC motor, is frequently used in electric vehicles because of its controllable speed and wide range of speeds (Jou et al., 2019).

The DC motor, a key component in energy systems, serves as a prime candidate for study due to its simplicity and efficiency in converting electrical energy into mechanical motion (Khalil & Grizzle, 2002).

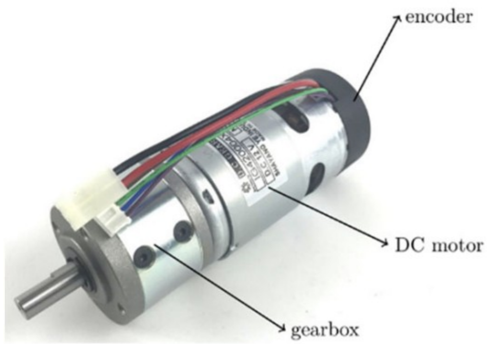

Figure 1. Motor DC

The DC motor is connected to an encoder to measure its rotation as pulse per rotation, and a gearbox is installed to reduce speed while increasing torque by transforming electrical energy into mechanical motion (Dorf & Bishop, 2011). The motor's characteristics consist of resistance, inductance, and back electromotive force (EMF), which are essential in controlling its performance (Nise, 2015).

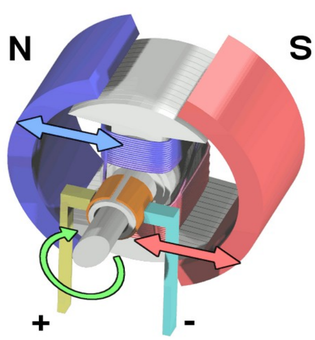

Figure 2. Magnet Motor DC

The DC motor works with two main components: the "stator" (permanent magnet) and the "armature" (rotor), where the rotor is connected to a power source through two rings called the commutator. The current supplied to the commutator creates a magnetic field that interacts with the stator, causing the rotor to rotate. As the rotor spins, the commutator switches polarity to ensure continuous rotation (Ogata, 2010).

2. Motor DC Data Sheet

The motor used in this research is the PittmanExpressTM DC motor type 14207S007, with a 24V specification. The detailed motor datasheet is as follows:

Table 1. Datasheet Motor DC

Assembly Data	Symbol	Units	Value
Reference Voltage	E	V	24
No-Load Speed	SNL	Rpm	3,211
Maximum Torque	TC	oz-in	50
Peak Torque	TPK	oz-in	410
Weight	WM	G	55

Other specifications, such as torque constant, back-EMF constant, and mechanical time constant, are essential for the motor's application in the research, as they determine the system's dynamic behavior and its interaction with control methods like LQR and LQT (Ogata, 2010; Dorf & Bishop, 2011).

a. First-Order Transfer Function

The general formula for the first-order transfer function is:

$$\frac{C(s)}{R(s)}=\frac{1}{Ts+1} \tag{7}$$

This formula can be expanded into partial fractions for analysis, where the transfer function for the first-order system is:

$$G(s)=\frac{K}{Ts+K} \tag{8}$$

Where k and τ represent the system constants that were derived from the motor's parameters.

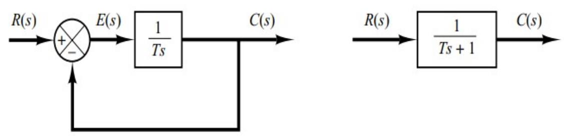

Figure 3. Order 1 Transfer Function

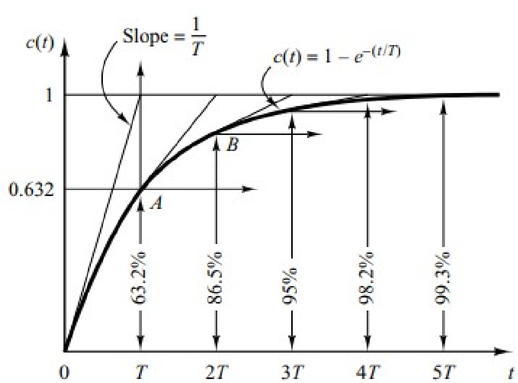

Figure 4. 1st order wave formation

b. Second-Order Transfer Function

For the second-order system, the transfer function is given by:

$$\frac{C(s)}{R(s)}=\frac{\omega_n^2}{s^2+2\zeta\,\omega_n s+\omega_n^2} \tag{9}$$

The behavior of the second-order system is determined by two parameters: damping ratio (ζ) and natural frequency (ωn). Based on these parameters, the system may exhibit underdamped, critically damped, or overdamped behavior (Khalil & Grizzle, 2002).

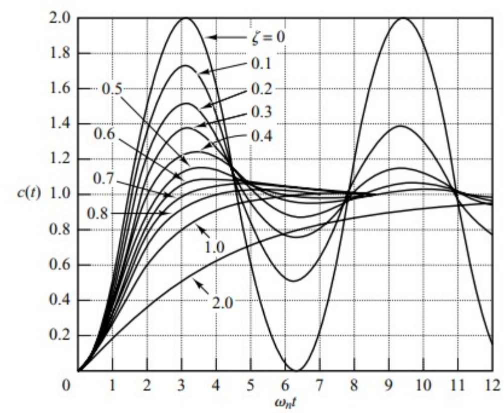

Figure 5. Order 2 waveforms based on value ζ

3. MATLAB Programming for LQR and LQT

To implement the LQR and LQT controllers for the DC motor, MATLAB programming is used to simulate the system's response. The DC motor's physical parameters, such as moment of inertia (J), damping ratio (b), torque constant (K), resistance (R), and inductance (L), are incorporated into the model. The MATLAB code and simulation results allow for optimization of the control parameters to achieve energy efficiency in maritime systems.

a. LQR and LQT Circuits

The LQR and LQT controllers are implemented using MATLAB Simulink. The LQR method optimizes the control by minimizing a quadratic cost function, while the LQT method is designed to track a specific trajectory while minimizing the energy consumption (Nise, 2015; Dorf & Bishop, 2011).

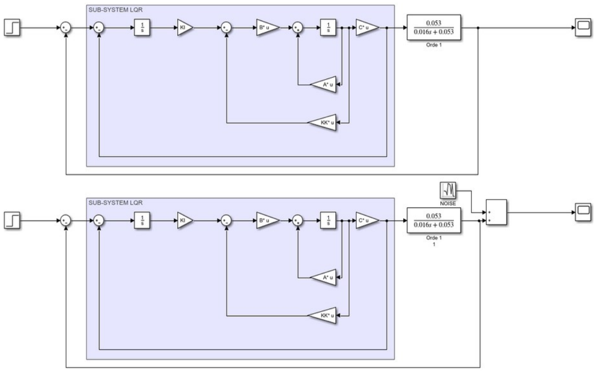

Figure 6. LQR Network

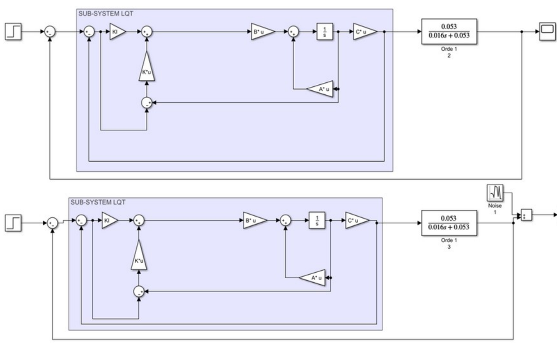

Figure 7. LQT Network

Results and Discussions

The results from the simulations run in MATLAB Simulink showed the effects of varying system parameters, such as noise influence on the system's output. The data was analyzed to evaluate the performance of both LQR and LQT methods in controlling the DC motor for energy efficiency in maritime electrical systems.

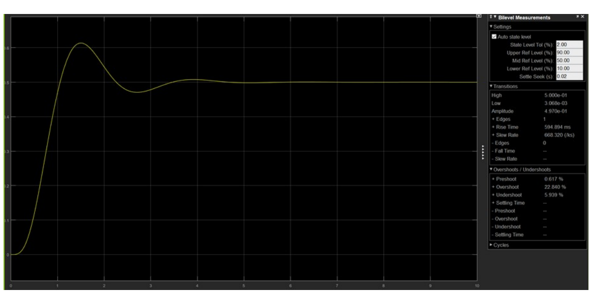

Figure 8. LQR Without Noise Order 1 Simulation Results

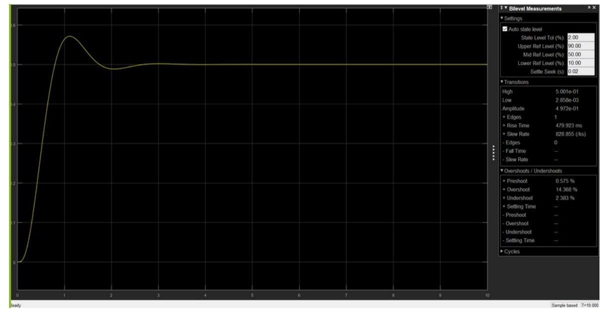

Figure 9. Results of LQR Without Noise Simulation Order 2

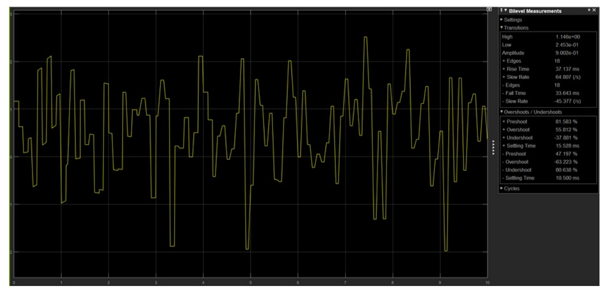

Figure 10. LQR With Noise Order 1 Simulation Results

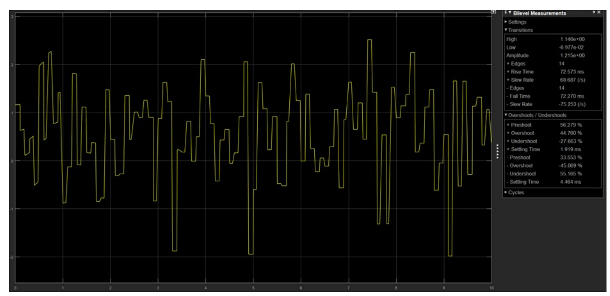

Figure 11. LQR With Noise Order 2 Simulation Results

The LQR simulation results revealed that the system without noise in Order 1 showed a peak value of 0.62 at the overshoot point, with a total overshoot percentage of 22.84%. The system reached a stable state after 5 seconds, with a rise time of 0.5 seconds, indicating a relatively fast system response. In contrast, Order 2 showed more stability, with a noticeable difference in time taken to reach the set-point, which was shorter by 2 seconds compared to Order 1.

The overshoot was lower at 14%, and the rise time was 0.48 seconds, demonstrating improved performance over Order 1. Both orders had similar set-point values, which were 50% smaller than the expected value. The noise analysis caused fluctuations in the output waveform, which did not stabilize, resulting in a loss of a fixed point. Despite similar waveform patterns between the two orders, Order 1 achieved a faster rise time, but Order 2 showed better stability with a smaller overshoot. The settling time for Order 1 and Order 2 were 1.421ms and 1.919ms, respectively.

Figure 12. Results of LQT Without Noise Simulation Order 1

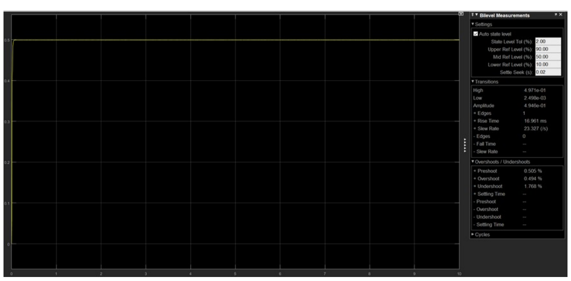

Figure 13. LQT Without Noise Order 2 Simulation Results

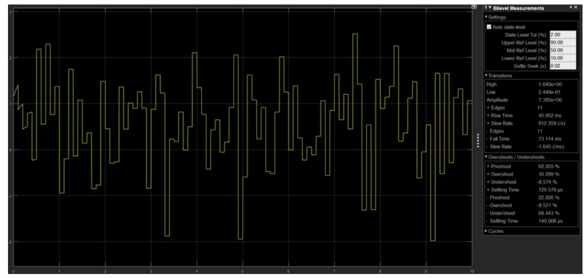

Figure 14. LQT With Noise Order 1 Simulation Results

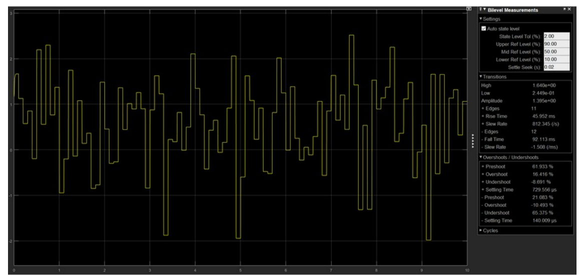

Figure 15. LQT with Noise Order 2 Simulation Results

The LQT simulation waveform demonstrated greater stability without significant overshoot. In Order 1, the system response was fast, with a rise time of 0.32ms and the system reaching stability in approximately 1 second. No significant spikes were observed. In Order 2, the system response was even faster, with a rise time of 0.16ms and stability achieved in under 1 second. However, the set-point target of 1 was not fully met, indicating the need for further optimization. These results show that the LQT method provides a faster and more stable system response compared to LQR.

Conclusion

The conclusions drawn from this study highlight the importance of mathematical modeling in evaluating energy efficiency solutions for maritime communities. Initially, the mathematical model was developed using Transfer Function calculations, which yielded first and second-order system parameters based on the datasheet of the selected DC motor. These parameters, such as moment of inertia, damping ratio, torque constant, resistance, and inductance, influenced the waveform characteristics, including ripple and amplitude, in the system's output.

Subsequently, a MATLAB program was developed using these parameters and the LQR and LQT control methods. The MATLAB Simulink simulations demonstrated that the LQR method produced a more stable waveform in Order 2, with less fluctuation in the output. The LQT method, however, showed a quicker and more stable system response, albeit with a slight mismatch in the set-point value.

These findings emphasize the potential of LQR and LQT methods in improving energy efficiency for maritime electrical systems. Despite the effectiveness of both methods, further modifications to the program, system design, or both are necessary to achieve the desired set-point values and optimal performance. This study, while focusing on theoretical analysis and simulation, presents valuable insights that can be directly applied to real-world energy systems in maritime communities, contributing to community service initiatives aimed at improving energy efficiency and sustainability.

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