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Performance Optimization of DC 054B-2 Motor with MATLAB-Based Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT) Method Approach for Control Engineering Applications

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Abstract

An accurate system model is essential as a basis for designing a reliable control system. This research aims to design an online system identification technique based on MATLAB to develop system models of Single Input Single Output (SISO), Single Input Multi Output (SIMO), Multi Input Single Output (MISO), and Multi Input Multi Output (MIMO). As a case study, the DC motor type 054B-2 was used to simulate SISO, SIMO, MISO, and MIMO systems in the first and second orders. In the implementation of a control system, external interference in the form of noise is often a major challenge, which can lead to high overshoot and affect system stability. Therefore, the system identification technique is designed to consider the influence of noise, using a MATLAB Simulink-based approach. This research also utilizes the Linear Quadratic Regulator (LQR) method as an optimal control technique that has been widely applied in industry, robotics, and various other engineering fields. The advantage of LQR lies in its ability to provide optimal solutions for systems defined in the context space, as expressed by Yul and Nazaruddin (2018). In addition, the Linear Quadratic Tracker (LQT) method is applied as an alternative, with the ability to follow (tracking) the reference path provided through system input. This method is particularly relevant for applications where tracking reference signals is a priority, as explained by Andria et al. (2014). The simulation results show that the LQR-based approach is able to reduce overshoot and improve system stability, while LQT provides high accuracy in dynamic signal tracking. This research has made a significant contribution to the development of optimal control techniques for DC motor-based applications, as well as opening up opportunities for further application in the field of modern control engineering.

Keywords: MATLAB, Simulink, DC Motor, Control System, LQR, LQT

1. Introduction

Control system optimization is an effort to produce a system with optimal performance that is in accordance with physical limitations and design requirements. In this context, the performance index-based optimization approach is a solution to minimize system deviation from its ideal condition. The application of optimization methods, such as Linear Quadratic Regulator (LQR) and Linear Quadratic Tracking (LQT), provides a robust framework for state-based system control.

DC motors (direct current motors) were chosen as the object of research because of their advantages in speed stability, efficiency, and ease of control. In addition, DC motors are often used in industrial applications, robotics, and electrical experiments (Muhardian & Krismadinnata, 2020). Its working principle is based on the interaction between the magnetic field of the rotor and the stator, which creates rotational motion. With the advantages of smooth operating sound and the ability to achieve stable speeds, DC motors are one of the mechanical devices that are easy to integrate with modern controllers (Atika & Wati, 2016). However, periodic maintenance is still necessary to maintain optimal performance, especially in parts that are prone to damage.

Mathematical models are the basis for the design of efficient control systems. The two main approaches in mathematical model development involve MATLAB-based observational data analysis and simulation. In this study, the DC motor type 054B-2 is used as a plant for the simulation of first- and second-order systems. The first order describes a system with one dominant variable, while the second order includes more variables to accommodate higher complexity (Rohman & Izaty, 2021). These mathematical simulations allow designers to efficiently evaluate system characteristics before direct implementation on real systems, thereby reducing operational risks and costs (Atika & Wati, 2016).

LQR is an optimization method designed to minimize the quadratic integral of excess numbers in a linear system. This method produces optimal initial state feedback with constant feedback acquisition. In its applications, LQR has proven to be effective in various fields of engineering, including industrial control and robotics (Bu et al., 2019). As a complement, the LQT method was introduced to enable system control by

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following specific reference paths with precision. This method is particularly relevant for applications that require dynamic tracking on control objects, as revealed by Andria et al. (2014).

In this study, DC motor type 054B-2 is used to implement LQR and LQT methods using MATLAB and Simulink. By utilizing the motor datasheet as a parameter reference, this study aims to evaluate the performance of this optimization method in improving the stability and accuracy of the control system. This research is expected to contribute to the development of optimal control techniques that are applicable to the needs of industry and modern techniques.

2. Material and methods

2.1. Material

DC motors are an essential component in a wide range of control engineering applications. Its ability to generate high torque and fast response makes it a top choice in applications such as robotics, industrial automation, and electric transportation systems (Sutrisno et al., 2019). The working principle of DC motors, which involves the interaction between the stator and rotor magnetic fields, allows for precise control of speed and torque through the use of modern control techniques such as LQR and LQT (Prasetyo & Nugraha, 2020). In the context of control engineering, dynamic system modeling is a crucial step for analysis and design. Accurate mathematical models provide the basis for system performance evaluation and optimal control algorithm design. The space-based approach of state became popular due to its ability to represent complex systems in a more structured form (Nugraha et al., 2020). MATLAB and Simulink are often used to facilitate modeling and simulation of dynamic systems because they provide flexible and accurate tools for analysis (Andria et al., 2021).

Linear Quadratic Regulator (LQR) is an optimal control method designed to minimize quadratic cost functions, reflecting the trade-off between control energy and deviation from the reference path. This method has been widely used in engineering applications due to the stability and efficiency it offers (Rahman et al., 2019). In the context of DC motors, LQRs can be used to maintain rotational speed stability and minimize the effects of external interference (Santoso et al., 2021). As a complementary method, Linear Quadratic Tracking (LQT) is designed to track reference paths with precision. In the application of control techniques, this method is often applied to systems with dynamic inputs to ensure that the system output remains on the desired path despite interference or parameter changes (Sutrisno et al., 2020). MATLAB itself is a very useful software in the development and evaluation of control systems. Simulations using MATLAB allow researchers to evaluate system performance without having to test on the hardware directly, thereby reducing the cost and risk of damage to real devices (Setiawan et al., 2022). With MATLAB, testing LQR and LQT methods on DC motors can be performed easily, providing in-depth insight into the characteristics of the system (Prasetyo et al., 2020).

2.2. Methods

2.2.1 Research Stages

In this study, the initial stage carried out is the selection of a research object in the form of a DC motor type 054B-2. The selection of this motor is based on the consideration of technical specifications relevant to the needs of the experiment. The DC 054B-2 motor datasheet of the PITMAN DC Motors series is used as the main reference in research to ensure data accuracy and modeling validation.

The next stage is a mathematical calculation based on the technical specifications of the motor that has been determined. This study uses two computational approaches, namely order 1 and order 2, to produce a mathematical model that is close to 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):

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

With τ as the torque (in Nm) and I as the current (in A). Based on the datasheet, a torque of 0.052 Nm and a current of 1.7 A are used to calculate the value of the constant K. The results of this calculation are then substituted into Equation (1) to obtain the 1st order transfer function.

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 ωn is the angular velocity calculated using Equation (4):

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

The frequency (f) is taken from the available DC motor specifications. The results of the calculation of the angular velocity ωn and the damping ratio ζ then used to obtain the 2nd order transfer function.

2.2.2 Simulation with MATLAB Simulink

After obtaining the mathematical model, the research continues to the simulation stage using MATLAB Simulink. The Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT) models are designed to analyze the performance of DC motor control systems. Simulations were performed with and without the addition of noise to test the robusta of the system against interference.

The analysis of the simulation results includes a comparison of performance between LQR and LQT methods. Optimization parameters, such as stability, response time, and attenuation, are tested using an approach that suits the needs of the control system.

2.2.3 Modelling and Components Used

The mathematical model obtained from the 1st order and 2nd order transfer functions is applied using a MATLAB script, with key parameters such as moment of inertia (J), damping ratio (b), torque constant (K), resistance (R), and inductance (L). Here is a snippet of the MATLAB script for LQR and LQT optimization:

- System Optimization with 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);
```

- System Optimization with LQT

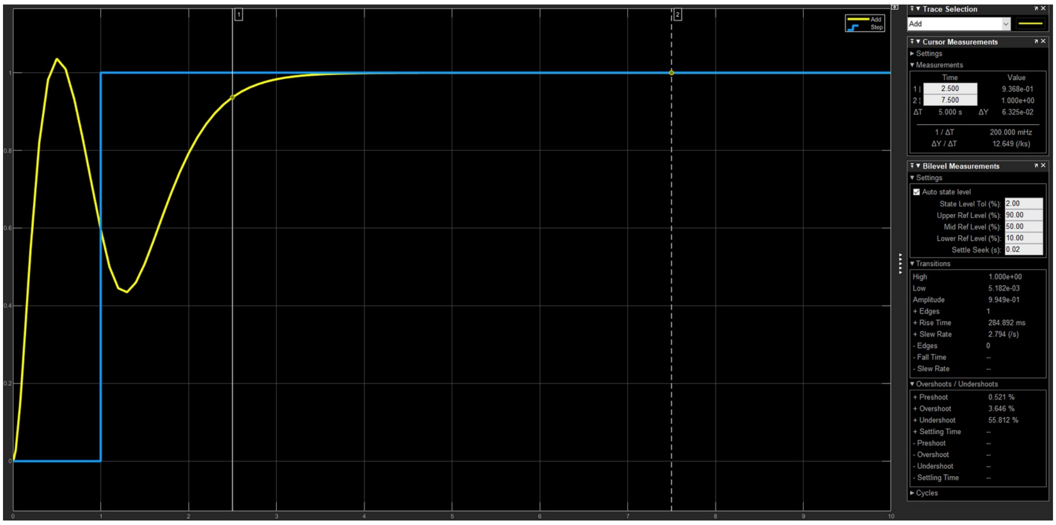
```
Clear;
CLC;
J = 0.000016;
b = 0.000011;
K = 0.03;
R = 1.03;
L = 0.0016;

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 carried out with various scenarios, including the influence of noise on the plant to evaluate the control performance. The simulation components used include MATLAB Simulink elements such as LQR and LQT subsystems with and without noise.

3. Results and discussion

This study produced an in-depth simulation related to the performance of the DC 054B-2 motor using the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT) approaches. Here is a breakdown of the simulation results that illustrate the performance of both methods under normal conditions (no noise) and with noise.

3.1. Simulation Results of Linear Quadratic Regulator (LQR) Without Noise



	Time		Value
1	2.500		9.368e-01
2	7.500		1.000e+00
ΔT	5.000 s	ΔY	6.325e-02

1 / ΔT 200.000 mHz
ΔY / ΔT 12.649 (/ks)

☑ Auto state level
State Level Tol (%): 2.00
Upper Ref Level (%): 90.00
Mid Ref Level (%): 50.00
Lower Ref Level (%): 10.00
Settle Seek (s): 0.02

High	1.000e+00
Low	5.182e-03
Amplitude	9.949e-01
+ Edges	1
+ Rise Time	284.892 ms
+ Slew Rate	2.794 (/s)
- Edges	0
- Fall Time	--
- Slew Rate	--

+ Preshoot	0.521 %
+ Overshoot	3.646 %
+ Undershoot	55.812 %
+ Settling Time	--
- Preshoot	--
- Overshoot	--
- Undershoot	--
- Settling Time	--

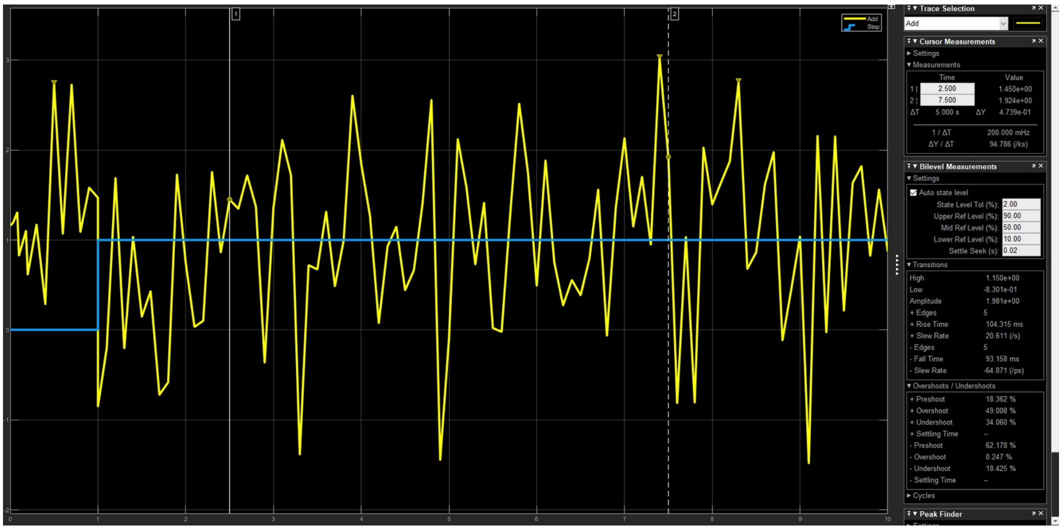
Figure 1. LQR Response Step Display Without Noise

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

- Maximum amplitude: 0.994
- Stabilization time: 4 seconds
- Overshoot: 3,646%
- Undershoot: 55,821%

These results show that the system achieves stability with an amplitude close to the set point. However, a large undershoot value indicates that the initial response of the system is not optimal.

3.2. LQR Simulation Results Using Noise



Add

	Time		Value
1	2.500		1.450e+00
2	7.500		1.924e+00
ΔT	5.000 s	ΔY	4.739e-01

1 / ΔT 200.000 mHz
ΔY / ΔT 94.786 (/ks)

☑ Auto state level
State Level Tol (%): 2.00
Upper Ref Level (%): 90.00
Mid Ref Level (%): 50.00
Lower Ref Level (%): 10.00
Settle Seek (s): 0.02

High	1.150e+00
Low	-8.301e-01
Amplitude	1.981e+00
+ Edges	5
+ Rise Time	104.315 ms
+ Slew Rate	20.611 (/s)
- Edges	5
- Fall Time	93.158 ms
- Slew Rate	-64.871 (/ps)

+ Preshoot	18.362 %
+ Overshoot	49.008 %
+ Undershoot	34.060 %
+ Settling Time	--
- Preshoot	62.178 %
- Overshoot	0.247 %
- Undershoot	18.425 %
- Settling Time	--

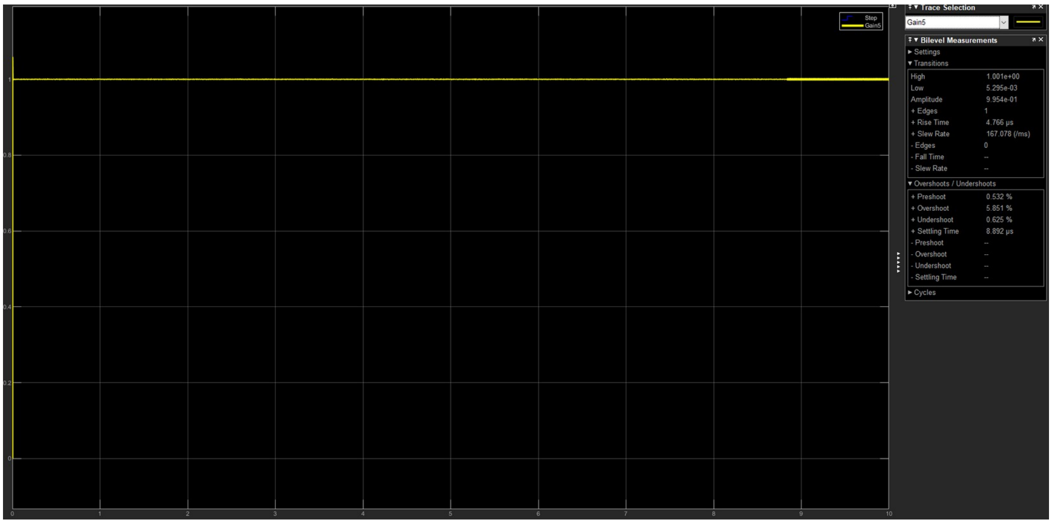
Figure 2. LQR Step Response Display (with Noise)

Figure 2 shows the simulation results with the noise added to the system.

- Maximum amplitude: 1.98
- Overshoot: 49%
- Undershoot: 34%

Compared to no-noise conditions, noise significantly affects the stability of the system, resulting in much greater overshoot and undershoot.

3.3. Noise Free LQT Simulation Results



Gain5

High	1.001e+00
Low	5.295e-03
Amplitude	9.954e-01
+ Edges	1
+ Rise Time	4.766 µs
+ Slew Rate	167.078 (/ms)
- Edges	0
- Fall Time	--
- Slew Rate	--

+ Preshoot	0.532 %
+ Overshoot	5.851 %
+ Undershoot	0.625 %
+ Settling Time	8.892 µs
- Preshoot	--
- Overshoot	--
- Undershoot	--
- Settling Time	--

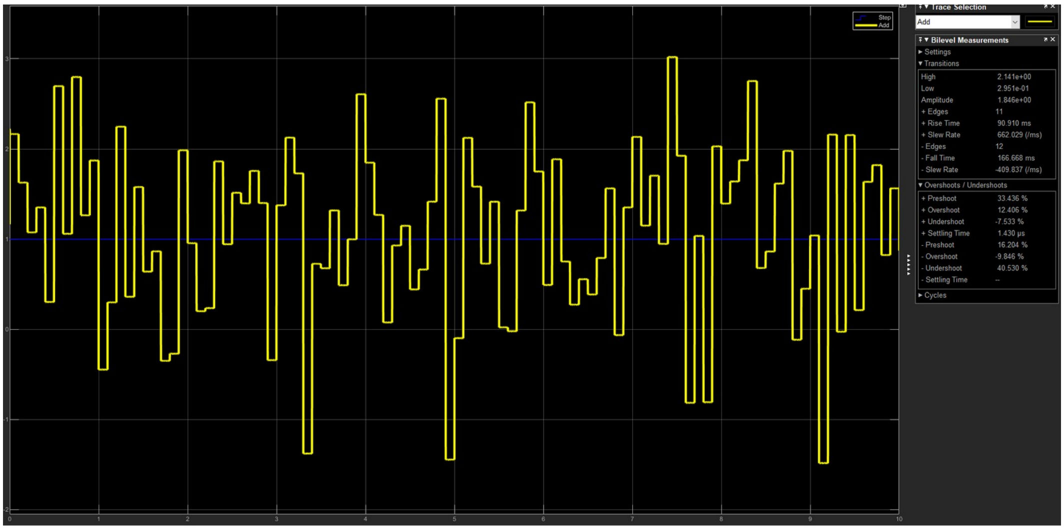
Figure 3. LQT Step Response Display Without Noise

Under normal conditions without noise, Figure 3 shows a graph of the system's response using the LQT method:

- Maximum amplitude: 0.995
- Rise time: 4,766 µs
- Overshoot: 5,851%
- Undershoot: 0.625%

The simulation results show stable performance with minimal overshoot and undershoot values, indicating the advantages of this method in reducing interference.

3.4. LQT Simulation Results Using Noise



```
▼ Transitions
High              2.141e+00
Low               2.951e-01
Amplitude         1.846e+00
+ Edges           11
+ Rise Time       90.910 ms
+ Slew Rate       662.029 (/ms)
- Edges           12
- Fall Time       166.668 ms
- Slew Rate       -409.837 (/ms)
▼ Overshoots / Undershoots
+ Preshoot        33.436 %
+ Overshoot       12.406 %
+ Undershoot      -7.533 %
+ Settling Time   1.430 µs
- Preshoot        16.204 %
- Overshoot       -9.846 %
- Undershoot      40.530 %
- Settling Time   --
```

Figure 4. LQT Step Response Display Using Noise

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

- Maximum amplitude: 1,846
- Rise time: 90.91 ms
- Overshoot: 12,406%
- Undershoot: -7,533%

These results show that noise affects the stability of the response, but the resulting amplitude is still close to the set point, with smaller overshoots and undershoots than the LQR method.

3.5. Comparison Results of Normal Conditions and Noise

Table 1 below summarizes the comparison of the simulation results for both methods under normal conditions and with noise:

Table 1. Comparison of Normal Conditions and noise based on simulation results

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 4.766us. *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%.

4. Conclusion

Based on the results of the simulations carried out, the Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT) methods show different characteristics and performance in controlling DC 054B-2 motors. The LQR method produces a stable response graph with an amplitude close to the set point, but has a disadvantage in the form of significant undershoot values, especially in the absence of noise. The addition of noise to the LQR method causes a significant increase in overshoot and undershoot, resulting in decreased system stability. In contrast, the LQT method shows superior performance with faster response times and more stable response graphs, both in no-noise and no-noise conditions. Although the addition of noise affects the amplitude stability, the overshoot and undershoot values in the LQT method are still smaller than those of the LQR method. Overall, the LQT method has proven to be more effective at maintaining system stability and mitigating interference than the LQR method, making it a better choice for DC motor control applications.

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