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Simulation Analysis of System Optimization Using an EC-Max 40 Type DC Motor Plant

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Abstract

A control system functions to regulate one or more variables, ensuring they remain at specific values or within desired limits. The primary aim is to achieve optimal system performance through effective control strategies. In this study, system optimization is explored within a closed-loop configuration using a DC motor as the plant. The motor selected for this analysis is the EC-Max 40, a direct current motor that converts electrical energy into mechanical motion. Utilizing the motor's datasheet, a first-order mathematical model is developed and implemented in Matlab Simulink for simulation purposes. The system design incorporates both Linear Quadratic Regulator (LQR) and Linear Quadratic Tracker (LQT) methods to evaluate and compare their performance. The analysis focuses on the step response of the system observing how the output behaves in response to input variations both under ideal conditions and in the presence of noise. The simulations reveal that both LQR and LQT methods produce similarly effective results; however, the LQT approach demonstrates a faster convergence to stability compared to the LQR method.

Keyword: DC Motor, LQR, LQT, Noise, Optimization

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1. Introduction

In the evolution of science and technology, advancements in automatic control theory and practice have significantly simplified the process of achieving desired system performance levels [1]. A control system refers to a mechanism for regulating one or more quantities such as variables or parameters so they remain at specific values or within a predetermined range [2]. From the perspective of tools and instrumentation, a control system is composed of various physical components arranged to direct energy flow into a machine or process to fulfill the intended target. The primary goal of such systems is optimization, which is inherently linked to the function of the

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control system itself. This concept aligns closely with optimal control systems, which focus on selecting performance indices and designing controllers that yield optimal results within physical limitations [3]. Broadly speaking, optimal control theory involves strategies aimed at minimizing or maximizing a performance index function [4].

Control systems are generally categorized into two types: open-loop and closed-loop systems [5]. In an open-loop system, the output signal does not influence the control action, as there is no feedback from the output to the input [6]. In contrast, a closed-loop control system enables the output to directly affect the control action through a feedback loop [7].

This explores the application of a closed-loop control system to analyze the response behavior of a DC motor. A DC motor operates on direct current voltage and its rotational direction is determined by either the forward or reverse current flow, or by the polarity of the applied voltage [8]. DC motors are widely used due to their versatility and simplicity, making them suitable for various applications from industrial equipment and household appliances to children's toys and electronic instruments [9]. Given the high demand in industrial settings, implementing system optimization becomes essential as it provides a systematic approach for identifying the most effective solutions [10].

The DC motor employed in this study is the EC-Max 40 type, modeled using a first-order mathematical equation to serve as the system's plant. Simulations were conducted using LQR and LQT methods. The Linear-Quadratic Regulator (LQR) is a state-space control approach that relies on full system information. To achieve optimal gain values, it requires tuning of the Q and R weight matrices [11]. On the other hand, the Linear-Quadratic Tracker (LQT) addresses tracking problems in linear systems. It is designed to ensure that the system follows a predefined reference trajectory by minimizing a specified quadratic cost function. LQT incorporates both feedback and feedforward components, calculated using the Algebraic Riccati Equation (ARE) [12].

This research utilizes Simulink, a graphical extension of Matlab, to model and simulate the systems built using the LQR and LQT methods. In Simulink, systems are represented through block diagrams, including components such as transfer functions and summing junctions, along with virtual input and output devices like function generators and oscilloscopes [13]. The aim is to examine the step response—how the motor's output behavior shifts in response to input signals both in noise-free conditions and when system output is subjected to noise [14].

2. Research Method

2.1 DC Motor

A DC motor is a type of electric motor that operates using a direct current voltage source. It is one of the most commonly used actuators in various applications [15]. The direction in which a DC motor rotates is controlled by the direction of current flow either forward or reverse or by applying positive or negative voltage [16]. The speed of the motor, on the other hand, is influenced by variations or increases in the voltage applied to its windings [17][18]. DC motors offer the advantage of having both their direction and speed easily adjustable [19][20]. The motor’s rotation direction is managed by reversing the voltage polarity, while its speed is controlled by regulating the voltage level. In this practicum, the DC motor used is the EC-Max 40 model, as shown in Figure 1.

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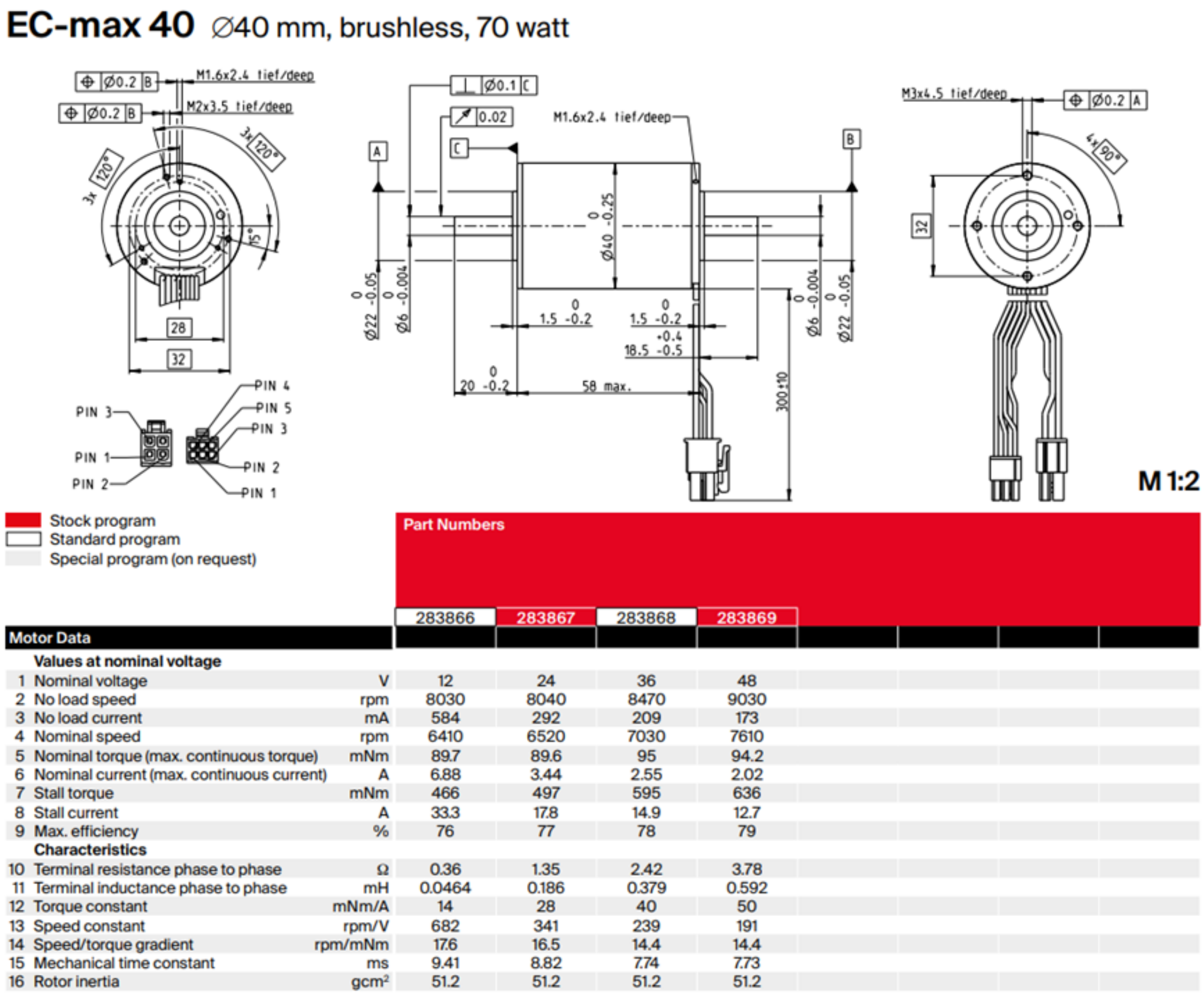
Figure 1. DC Motor EC-Max 40

2.2 DC Motor Specification



EC-max 40 Ø40 mm, brushless, 70 watt

🟥 Stock program
☐ Standard program
Special program (on request)

Motor Data		Part Numbers 283866	283867	283868	283869
Values at nominal voltage					
1 Nominal voltage	V	12	24	36	48
2 No load speed	rpm	8030	8040	8470	9030
3 No load current	mA	584	292	209	173
4 Nominal speed	rpm	6410	6520	7030	7610
5 Nominal torque (max. continuous torque)	mNm	89.7	89.6	95	94.2
6 Nominal current (max. continuous current)	A	6.88	3.44	2.55	2.02
7 Stall torque	mNm	466	497	595	636
8 Stall current	A	33.3	17.8	14.9	12.7
9 Max. efficiency	%	76	77	78	79
Characteristics					
10 Terminal resistance phase to phase	Ω	0.36	1.35	2.42	3.78
11 Terminal inductance phase to phase	mH	0.0464	0.186	0.379	0.592
12 Torque constant	mNm/A	14	28	40	50
13 Speed constant	rpm/V	682	341	239	191
14 Speed/torque gradient	rpm/mNm	17.6	16.5	14.4	14.4
15 Mechanical time constant	ms	9.41	8.82	7.74	7.73
16 Rotor inertia	gcm^2	51.2	51.2	51.2	51.2

Figure 2. Data Sheet DC Motor EC-Max 40

At this stage, identification is carried out regarding the specifications of the DC Motor that will be researched. The form of the DC Motor that was researched was a brushless motor with the name and type EC-Max 40. The following is the datasheet of the DC Motor EC-Max 40.

Table 1. Specification DC Motor

Specification DC Motor EX-Max 40	
Rated Torque (τ)	89,6 mNm = 0,0896 Nm
No Load Current(A)	292mA= 0,292 A
Rated Current(A)	3,44 A
Voltage (V)	24 V
Speed (rpm)	341 rpm = 35,7 m/s
Rotor Inertia ($\boldsymbol{J_R}$)	51,2 gcm^2
Resistance (R)	1,35 Ω
Inductance (L)	0,186mH
Redaman Sistem Mekanik (B)	0,1 Nms

2.3 First Order DC Motor Modeling

Based on the data sheet above, it can be used as a reference for determining the mathematical model of the 1st order system of the EC-Max 40 DC motor, which can be seen from the magnitude of the variable s (in the Laplace transformation). A system can be said to be first order if the transfer function has a variable s with the highest power of one as follows

General equation of 1st order transfer function:

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

Based on the datasheet of the EC-Max 40 DC motor, the 1st order equation is obtained Where τ = K.i so that the 1st order equation of the DC motor is obtained:

$$K = \frac{\tau}{i} = \frac{0{,}0896}{3{,}44} = 0{,}026 \tag{2}$$

$$G(s) = \frac{0{,}026}{0{,}0896s + 1} \tag{3}$$

2.4 Matlab LQR Program on EC-Max 40 DC Motor

In the optimizing the EC-Max 40 DC motor system using the LQR method, a matlab script program is needed to simulate the system on Simulink. The following is the matlab script program used:

```
clear; clc;
% Model Motor DC
J = 51.2 ; b = 0.1 ; K = 0.026 ; R = 1.35 ; L = 0.000186 ;
% J = Moment of friction, b = Damping ratio, K = constant, R = resistance, L = Inductance
A = [-b/J K/J; -K/L -R/L];
B = [0; 1/L];
C = [1 0];

AA = [ A zeros(2,1); -C 0];
BB = [B;0];
```

```
% Pole Placement
J = [-3 -4 -5];
K = acker(AA,BB,J)
KI = -K(3);
KK = [K(1) K(2)];

% Matrix LQR
Q = [1 0 0;
   0 1 0;
   0 0 1000];
R = [1] ;

K_lqr = lqr(AA,BB,Q,R)
KI2=-K_lqr(3);
KK2=[K_lqr(1) K_lqr(2)];
```

2.5 Matlab LQT Program on EC-Max 40 DC Motor

In the optimizing the EC-Max 40 DC motor system using the LQT method, a matlab script program is needed to simulate the system on Simulink. The following is the matlab script program used:

```
clear;
clc;
% Model Motor DC
J = 51.2    ; b= 0.1 ; K= 0.026 ; R= 1.35 ; L = 0.000186 ;
% J = Moment of friction, b = Damping ratio, K = constant, R = resistance, L = Inductance
A = [-b/J K/J; -K/L -R/L];
B = [0; 1/L];
C = [1 0]
Q=10; R=0.0000000001; %0.00000000000001
W=C'*Q; %
[S,o,m,n]=care(A,B,C'*Q*C,R) %m=v(t) %S=P
K=inv(R)*B'*S %feedback Gain
ACL=(A-B*K)'
L=inv(R)*B' %model following gain
```

2.6 System Design in the Simulator

Following the development of the mathematical model for the EC-Max 40 DC motor, along with Matlab script programming and system requirement analysis, the next step involves designing the system using both the LQR and LQT methods. This design is implemented under two scenarios: without the presence of noise and with added noise introduced through the Random Number component. The system models based on the LQR and LQT methods are constructed and simulated within the Simulink environment, as illustrated below.

- EC-Max 40 DC Motor Circuit 1st Order

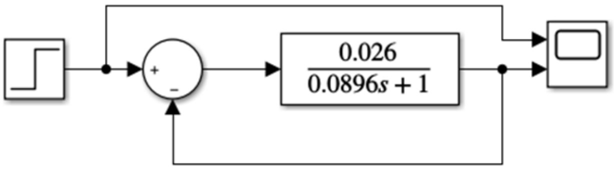


Figure 3. DC Motor Circuit 1st Order

- LQR circuit

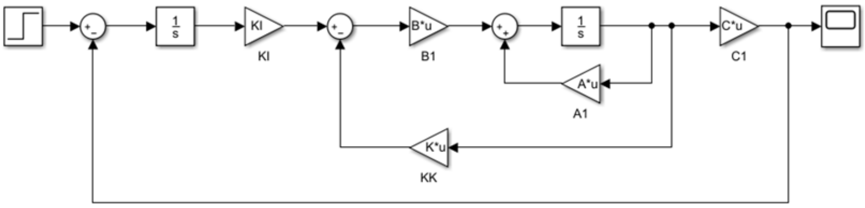


Figure 4. LQR circuit

- Subsystem LQR circuit without noise

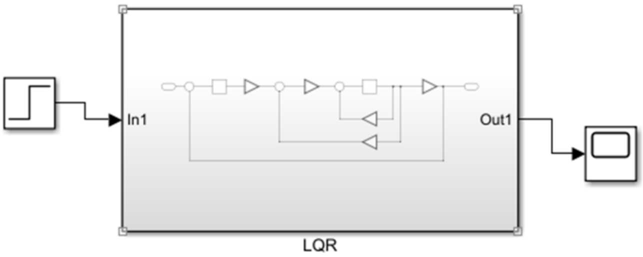


Figure 5. Subsystem LQR circuit without noise

- Subsystem LQR circuit with noise

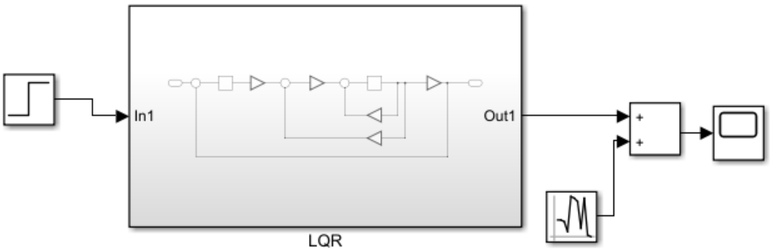


Figure 6. Subsystem LQR circuit with noise

- LQT circuit

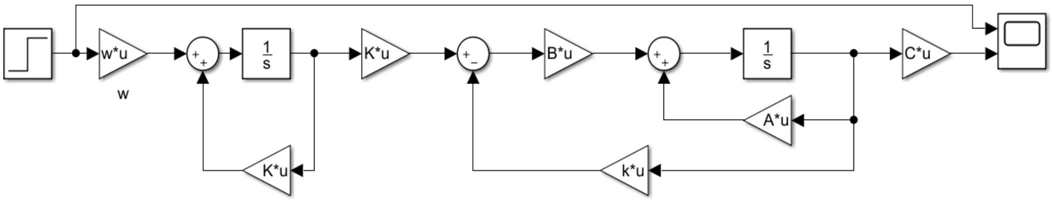


Figure 7. LQT circuit

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- Subsystem LQT circuit without noise

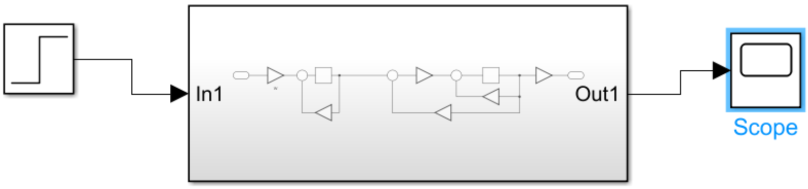


Figure 8. Subsystem LQT circuit without noise

- Subsystem LQT circuit with noise

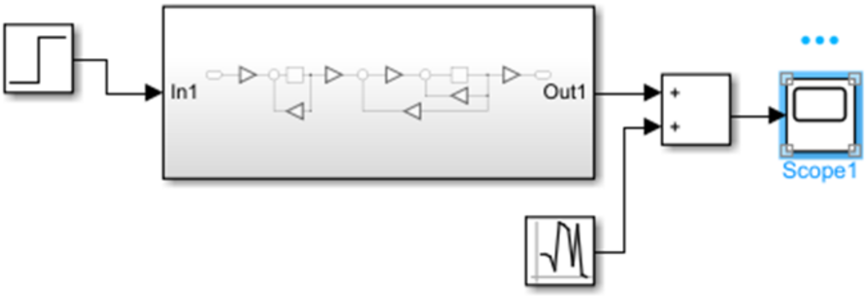
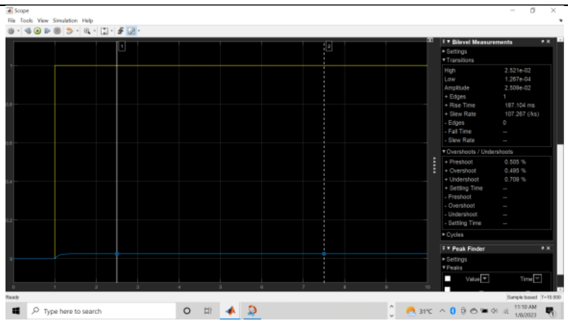


Figure 9. Subsystem LQT circuit with noise

3. Results And Discussion

3.1. Result simulation wave

Table 1. LQR and LQT Circuit Output Graph on EC-Max 40 DC Motor

No	Circuit	Simulation
1.	Motor DC EC-Max 40 Order 1	 Bilevel Measurements Transitions High 2.521e-02 Low 1.267e-04 Amplitude 2.509e-02 + Edges 1 + Rise Time 187.104 ms + Slew Rate 107.267 (/ks) - Edges 0 - Fall Time -- - Slew Rate -- Overshoots / Undershoots + Preshoot 0.505 % + Overshoot 0.495 % + Undershoot 0.709 % + Settling Time -- - Preshoot -- - Overshoot -- - Undershoot -- - Settling Time -- Cycles Peak Finder Settings Peaks Value Time Sample based T=10.000
2.	LQR without *Noise*	 Bilevel Measurements Transitions High 9.950e-01 Low 5.000e-03 Amplitude 9.900e-01 + Edges 1 + Rise Time 1.109 s + Slew Rate 714.182 (/ks) - Edges 0 - Fall Time -- - Slew Rate -- Overshoots / Undershoots + Preshoot 0.505 % + Overshoot 0.505 % + Undershoot 1.244 % + Settling Time -- - Preshoot -- - Overshoot -- - Undershoot -- - Settling Time -- Cycles Signal Statistics Value Time Max 1.000e+00 10.000 Min 0.000e+00 0.000e+00 Sample based T=10.000

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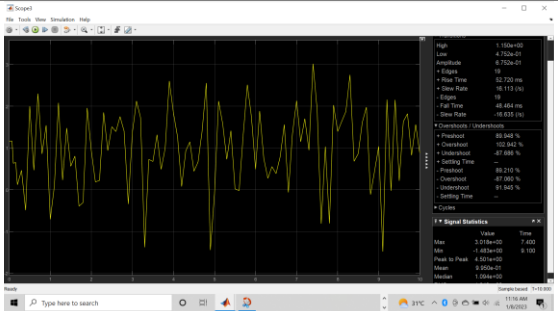
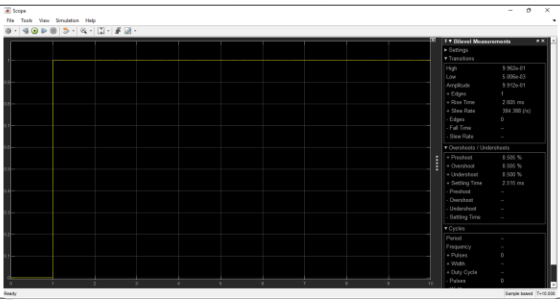
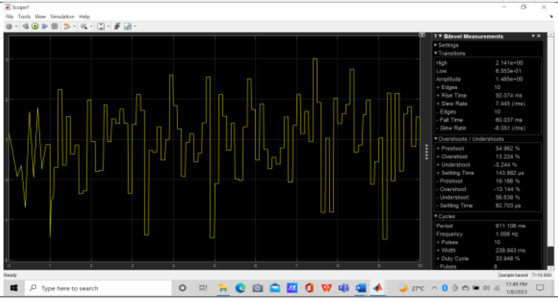
3.	**LQR with *Noise***	 High 1.150e+00 Low 4.752e-01 Amplitude 6.752e-01 + Edges 19 + Rise Time 52.720 ms + Slew Rate 16.113 (/s) - Edges 19 - Fall Time 48.464 ms - Slew Rate -16.635 (/s) Overshoots / Undershoots + Preshoot 89.948 % + Overshoot 102.942 % + Undershoot -87.686 % + Settling Time -- - Preshoot 89.210 % - Overshoot -87.060 % - Undershoot 91.945 % - Settling Time -- Cycles Signal Statistics Value Time Max 3.018e+00 7.400 Min -1.483e+00 9.100 Peak to Peak 4.501e+00 Mean 9.950e-01 Median 1.094e+00
4.	LQT without *Noise*	 Bilevel Measurements Settings Transitions High 9.962e-01 Low 5.006e-03 Amplitude 9.912e-01 + Edges 1 + Rise Time 2.605 ms + Slew Rate 304.388 (/s) - Edges 0 - Fall Time -- - Slew Rate -- Overshoots / Undershoots + Preshoot 0.505 % + Overshoot 0.505 % + Undershoot 0.500 % + Settling Time 2.515 ms - Preshoot -- - Overshoot -- - Undershoot -- - Settling Time -- Cycles Period -- Frequency -- + Pulses 0 + Width -- + Duty Cycle -- - Pulses 0
5.	LQT with *Noise*	 Bilevel Measurements Settings Transitions High 2.141e+00 Low 6.553e-01 Amplitude 1.485e+00 + Edges 10 + Rise Time 60.074 ms + Slew Rate 7.445 (/ms) - Edges 10 - Fall Time 60.037 ms - Slew Rate -6.051 (/ms) Overshoots / Undershoots + Preshoot 54.962 % + Overshoot 13.224 % + Undershoot -5.244 % + Settling Time 143.882 µs - Preshoot 19.186 % - Overshoot -13.144 % - Undershoot 56.638 % - Settling Time 82.703 µs Cycles Period 911.106 ms Frequency 1.098 Hz + Pulses 10 + Width 239.943 ms + Duty Cycle 33.948 % - Pulses 9

Table 2. LQR and LQT System Optimization Simulation Data on EC-Max 40 DC Motor

No	Circuit	Responses
1.	DC Motor EC-Max 40 Order 1	Risetime: 187.104 ms Amplitude: 0.025 Overshoot: 0.495% Undershoot: 0.709%
2.	LQR without Noise	Risetime: 1.109 s Amplitude: 0.99 Overshoot: 0.505% Undershoot: 1.244 %
3.	LQR with Noise	Risetime: 52.720 ms Amplitude: 6.752 Overshoot: 109.942% Undershoot: -87.686%
4.	LQT without Noise	Risetime: 2.6 s Amplitude: 0.99 Overshoot: 0.5% Undershoot: 0.5%

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5	LQT with Noise	Risetime: 50.074 ms Amplitude: 1,485 Overshoot: 13.224% Undershoot: 5.244%

The simulation analysis conducted on the EC-Max 40 DC motor highlights the performance characteristics of the system under various control strategies and operating conditions. Initially, the open-loop system response, as depicted in the simulation of the first-order model of the EC-Max 40 motor, demonstrates suboptimal behavior. The step response shows a low amplitude of approximately 0.025 and a rise time of 187.104 ms, coupled with minor overshoot (0.495%) and undershoot (0.709%). These results indicate the system's inability to reach the designated setpoint effectively, reflecting the limited dynamic performance of the motor when no control optimization is applied. The sluggish rise and low amplitude suggest that the system suffers from poor responsiveness and tracking accuracy, necessitating the implementation of a suitable control strategy.

Subsequent simulations incorporating Linear Quadratic Regulator (LQR) control show a marked improvement. In the noise-free scenario, the LQR-optimized system attains an amplitude of approximately 0.99 (rounded to 1), indicating successful setpoint tracking. The rise time improves significantly to 1.109 seconds, while the overshoot and undershoot remain minimal at 0.505% and 1.244%, respectively. These findings confirm the effectiveness of LQR in enhancing system stability and response speed by minimizing the cost function associated with state deviations and control effort. However, under noisy conditions, the LQR system exhibits degraded performance. The output fluctuates significantly, achieving an amplitude of 6.752 with a very fast rise time of 52.720 ms. Notably, the system experiences a high overshoot of 109.942% and a considerable undershoot of -87.686%, indicating reduced robustness of the LQR controller in the presence of disturbances. Such instability under noise highlights the necessity for more robust control formulations when operating in uncertain environments.

In contrast, the Linear Quadratic Tracker (LQT) control strategy demonstrates slightly slower yet more stable behavior in the absence of noise. The LQT-controlled system reaches a steady amplitude of approximately 0.99 with a rise time of 2.6 seconds. Both overshoot and undershoot are contained at 0.5%, suggesting that LQT offers a smooth and controlled tracking response. The increased rise time, when compared to LQR, is a trade-off for improved precision in trajectory tracking, which is intrinsic to the LQT design that prioritizes reference trajectory following over speed. Under noisy conditions, the LQT system's response remains relatively stable compared to the LQR counterpart. The system achieves an amplitude of 1.485 and a rise time of 50.074 ms, with a moderate overshoot of 13.224% and undershoot of -5.244%. These values indicate that while LQT is not immune to noise-induced fluctuations, its performance degradation is less severe, confirming its robustness in noisy environments.

Overall, the comparative analysis demonstrates that while both LQR and LQT significantly enhance the performance of the EC-Max 40 DC motor, their effectiveness varies with the presence of noise. LQR offers faster response in ideal conditions but is more sensitive to disturbances, whereas LQT provides better robustness with slightly slower dynamics. Therefore, the choice between LQR and LQT should consider the trade-off between speed and robustness, especially in practical applications where noise and external disturbances are inevitable.

4. Conclusion

Based on the results of the practicum, several conclusions can be drawn. To formulate a first-order mathematical model of a DC motor and determine the variables required for LQR and LQT methods, it is essential to utilize the motor's datasheet, which provides values such as moment of inertia, motor constant, damping ratio, resistance, and inductance. From these parameters, a first-order transfer function was derived as $G(s) = 0{,}026/(0{,}089s + 1)$. By executing the Matlab script, key system variables such as A, B, C, and K were successfully generated in the workspace. The step response outcomes for the EC-Max 40 DC motor using both LQR and LQT optimization methods showed similar performance. However, the LQT method achieved system stability more rapidly than the LQR approach. Overall, the comparison and evaluation of both methods indicate that the optimized systems perform significantly better than the unoptimized first-order DC motor model. With the use of LQR and LQT optimization techniques, the EC-Max 40 motor is able to reach the setpoint, exhibit a stable response, achieve a faster rise time, and maintain low overshoot and undershoot values.

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