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Differences Between LQR and LQT Optimization Methods Regarding Output Response of Maxon EC-i 40 DC Motor

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ABSTRACT

DC motor is an electronic component that is very common in everyday life. In general, DC motors tend to slow down under load, reduce speed, and do not run at a constant speed. The speed of a DC motor can be adjusted by changing the input voltage. Therefore, a controller is needed to keep the speed of the DC motor stable when the load changes. One method used to improve the performance of DC motors is LQR (Linear Quadratic Regulator) and LQT (Linear Quadratic Tracker). LQR aims to make the motor response close to the desired set point by reducing overshoot and undershoot in the system. LQT, on the other hand, is a linear control system that allows the system output to follow the desired reference. The LQR method produces a response that is close to the desired set point without overshoot and undershoot. Without using the LQR method, the motor response is far from the desired set point and takes a long time. Meanwhile, the LQT method speeds up the motor response to about ±0.5 seconds, but there is a little overshoot and the response has little variation. Compared to the LQR method, the LQT method is considered better because it produces a faster response to reach the set point on the Maxon EC-I 40 70 Watt DC motor..

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

I.INTRODUCTION

DC motors are electronic components that are very commonly used in everyday life. An electric motor is an electromagnetic device that converts electrical energy into mechanical energy or motion [1]. The operating principle of a DC motor is to ensure that the direction of the rotor magnetic field is always opposite to the stator magnetic field so that they repel each other. The coil is driven by a strong electric current, creating a magnetic field in a certain direction around the anchor coil [2][3]. In general, DC motors run slowly under load, run slowly, and do not operate at a constant speed. The speed of a DC motor can be controlled by changing the input voltage [4][5]. For example, if the load increases and the DC motor slows down, the solution is to increase the speed again by increasing the input voltage of the DC motor. Therefore, a controller is needed to keep the speed of the DC motor constant.

Stable when the load changes. The basic function of the controller is to compare the actual value of the generator output with the reference input (desired value), identify the error, and generate a control signal that will reduce the error to a value close to zero [6][7].

One of the methods used to control DC motors to increase motor power is LQR (Linear Quadratic Regulator) and LQT (Linear Quadratic Follower) [8]. The function of LQR is to bring the motor response closer to the desired set point and reduce overshooting and overshooting that occurs in the system. The LQR control method has characteristics such as robustness, reliability, static gain generation, etc. By using this optimal control method in large systems with many inputs, effective control of many outputs can be achieved reliably and economically [9][10]. The linear quadratic tuning technique is used to design an optimal controller that minimizes a certain cost function and performance index [11].

LQT is a linear control system whose system output follows the desired reference trajectory [12].

Linear quadratic tracking (LQT) is a model-based tracking control mechanism that uses affine state feedback to provide optimal control effort.

LQT includes the usual state feedback of a linear dynamic system plus additional feedforward control provisions.

The feedforward control term depends on the reference signal vector [13].

Usually, LQT is used to track optimization problems related to the system [14]. In the Optimization of Automation Engineering Systems Course of Surabaya State Polytechnic of Shipbuilding, experiments were conducted to evaluate the impact of using the LQR and LQT methods on the output response generated by a DC motor. In addition, the experiment also includes the addition of disturbances (noise) to the system to determine whether the use of the LQR and LQT methods can reduce the impact of the disturbance on the motor response or whether the motor response remains affected by the given disturbance. In addition, we will also analyze the differences between the LQR and LQT optimization methods when applied to the same type of DC motor [15].

II.METHODOLOGY

2.1 DC Motor Identification Stages

At this stage the technical parameters of the DC motor being sought have been determined. The type of DC motor produced in this study is a brushless motor with the name and model Maxon EC-I 40 70 Watt. This is the technical data sheet of the Maxon EC-I 40 70 watt DC motor.

Motor Data		with Hall sensors 449469
Values at nominal voltage		
1 Nominal voltage	V	18
2 No load speed	rpm	10100
3 No load current	mA	354
4 Nominal speed	rpm	8230
5 Nominal torque (max. continuous torque)	mNm	68.7
6 Nominal current (max. continuous current)	A	3.93
7 Stall torque[1]	mNm	876
8 Stall current	A	52.5
9 Max. efficiency	%	84
Characteristics		
10 Terminal resistance phase to phase	Ω	0.343
11 Terminal inductance phase to phase	mH	0.18
12 Torque constant	mNm/A	16.7
13 Speed constant	rpm/V	572
14 Speed/torque gradient	rpm/mNm	11.7
15 Mechanical time constant	ms	2.98
16 Rotor inertia	gcm^2	24.2

From Figure 1, data can be taken regarding the specifications of the Maxon EC-I 40 70 Watt DC Motor which will be presented in Table 1.

Model	Data	Unit
Nominal Voltage	18	V
No load speed	10100	Rpm
No load current	354	Mom
Nominal Speed	8230	Rpm
Nominal torque	68.7	mNm
Nominal Current	8.93	A
Stall torque	876	mNm
Stall current	52.5	A
Maximum	84	%

efficiency		
Terminal Resistance	0.343	Ohm
Terminal inductance	0.18	mH
Torque constant	16.7	mNm/A
Speed constant	572	Rpm/mNm
Inertia rotor	24.2	gcm

From Table 1 above, the determination of the DC motor to be used is done through mathematical calculations that require variable values obtained from the DC motor specification sheet data.

2.2 Modeling of 2nd Order DC Motor

The second order DC motor model can be written mathematically as follows [16]:

$$G(s)=\frac{\omega n^2}{s^2+2\varsigma\omega ns+\omega n^2} \quad (1)$$

Information :

ζ = Damping Ratio (dB)

ωn = Natural Frequency (rad/s)

Where :

$$\omega n=2\pi f \quad (2)$$

$$\omega n=2\times 3{,}14\times 50=314\, rad/s$$

So the calculation for the Maxon EC-I 40 70 Watt DC motor based on the specifications from the datasheet obtained is:

$$G(s)=\frac{314^2}{s^2+2\times 0{,}1\times 314\,s+314^2} \quad (3)$$

$$G(s)=\frac{98596}{s^2+62.8\,s+98596} \quad (4)$$

2.3 Optimal Control of Linear Quadratic Regulator (LQR)

Linear Quadratic Regulator (LQR) is a technique used in modern control theory [20]. Such systems are analyzed using the state-space approach. This method is used in multi-input multi-output systems because of its simple state-space approach [18][19]. The general state-space equation for such systems can be formulated as follows:

$$X=AX+Bu \quad (5)$$

Basically, the LQR method aims to find a control signal u that optimizes the performance index J.

$$J=\int (X^T Q_X+u^T ¿ R_a)\,dt ¿ \quad (6)$$

The optimal control input law u* is found by LQR, and the Q and R matrices minimize the performance index. The ideal closed-loop control law is[17]:

$$u=-Kx \quad (7)$$

Where K is the ideal feedback gain matrix. The gain matrix reduces the performance index. It determines the exact location of the closed-loop poles to reduce it. The feedback gain matrix K depends on the matrices A, B, Q, and R. The feedback gain matrix K is obtained by solving the Riccati Algebraic Equation (ARE). The symmetric matrix is defined as P, and the positive definition matrix obtained from the solution of the ARE is defined as:

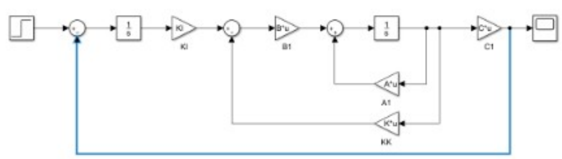
$$A^T P+PA-PBR^{-1}B^T P+Q=0 \quad (8)$$

$K=AX-BKx=(A-BK)x$ (9)

Substitute equations (8) and (9) to get

$x=AX-BKx=(A-BK)x$ (10)

The block diagram showing the LQR configuration is shown in Figure 2.



Gambar 2. Diagram Blok LQR
Sumber gambar: Penulis

2.4 LQR Matlab Program on Maxon EC-I 40 70 Watt DC Motor

% LQR SYSTEM OPTIMIZATION ON DC MOTOR

clear; clc;

% DC Motor Models

J=0.00000242 ; b=0.1 ; K=0.0167 ; R=0.343 ; L = 0.00018 ;

% J = Momentum, b = Damping ratio, K = constant, R = resistance, L =

% Inductance

A = [-b/JK/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)];

% LQR Matrix

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 Optimal Control of Linear Quadratic Tracker (LQT)

LQT is a combination of conventional state feedback from a linear dynamic system, along with an additional feedforward control term. The feedforward control component depends on the reference signal vector, r(t). The vector r(t) is expressed as follows:

$r(t)=[V_{ref}(t)0]\ pangkat\ T$ (11)

Where, is a reference voltage signal that changes over time. The LQT scheme aims to reduce the quadratic performance index to achieve optimal control decisions, which can be expressed in the following equation (Saleem et al., 2018).V_{ref}

$J=\frac{1}{2}\int_{0}^{T} ¿¿$ (12)

Where , Q and R are the weighting matrices for the intermediate and control states, respectively. These matrices are chosen with certain conditions; Q = QT ≥ 0 and R = RT>0. Since the cost function has a quadratic nature, the control signal is directly proportional to the square of the state variation. Therefore, if the state variation is large, then the minimization effort is also large, and as a result, the convergence rate will be faster.

The optimal affine control decision is evaluated through the mathematical expression presented in (Saleem et al., 2018), .

$$d(t) = -Kx(t) + K_{ff} v_{ref}(t) \quad (13)$$

Where,

$$K = R^{-1} B^T P \quad (14)$$

$$K_{ff} = R^{-1} B^T ¿ \quad (15)$$

K, the gain vector, helps to move the poles of the system to synthesize the best controller. Equation (14) shows that the ideal gain vector depends on the symmetric positive definite matrix, P. The matrix for the given system can be obtained by solving the Riccati Algebra Equation, shown in.

$$A^T P + PA - PBR^{-1} B^T P + H^T QH = 0$$
(16)

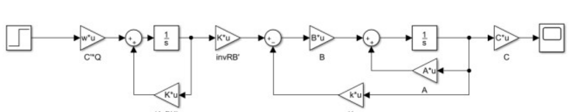


Figure 3. LQR Block Diagram

2.6 LQT Matlab Program on Maxon EC-I 40 70 Watt DC Motor

```
% LQR SYSTEM OPTIMIZATION ON DC MOTOR

clear; clc;

% DC Motor Models

J=0.00000242 ; b=0.1 ; K=0.0167 ; R=0.343 ; L = 0.00018 ;

% J = Momentum, b = Damping ratio, K = constant, R = resistance, L = Inductance


A = [-b/JK/J; -K/L -R/L];

B = [0;1/L];

C = [1 0];

D = 0;

Q=10000;

R=0.001;


%Ricatti Calculation

%S=P

[S,o,m,n]=care(A,B,C'*Q*C,R);

k = inv(R)*B'*S

w = C'*Q;

AB =(AB*k)';

ABT = AB';

RB=inv(R)*B';
```

2.7 System Block Diagram

2.7.1 Block Diagram of Second Order DC Motor Maxon EC-I 40 70 Watt

The purpose of the first order motor block diagram is to find out the original response results of the DC motor if the Maxon EC-I 40 70 Watt DC motor is used without using the method carried out in the Simulink software.

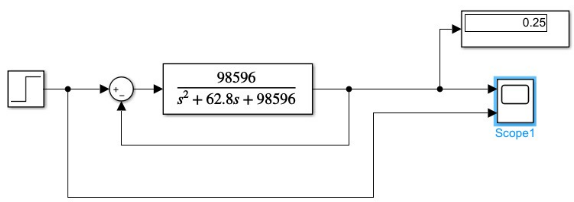


Figure 4. Block Diagram of Second Order DC Motor

Image source: Author

Figure 3 shows a second-order block diagram of a DC motor that has input and output. In the diagram, the transfer function can contain the modeling of a second-order DC motor because the input used is a step response type. To find out the maximum value of the response, the results will be displayed on the scope and display

2.7.2 LQR Block Diagram of Maxon EC-I 40 70 Watt DC Motor.

The LQR block diagram of the Maxon EC-I 40 70 Watt DC motor is used to test the response of the DC motor when the LQR optimization method is applied using Simulink software. The purpose is to understand the results of the DC motor response after the application of the LQR optimization method.

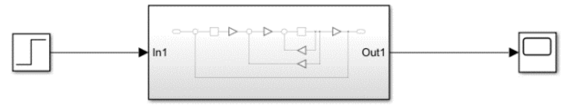


Figure 5. Block Diagram of Maxon EC-I 40 70 Watt DC Motor LQR
Image source: Author

2.7.3 Block Diagram of LQR DC Motor Maxon EC-I 40 70 Watt with Noise

In the LQR block diagram of the Maxon EC-I 40 70 Watt DC motor in the presence of noise, the main objective is to identify the response of the DC motor when the LQR optimization method is applied to the system and when noise is added to the system.

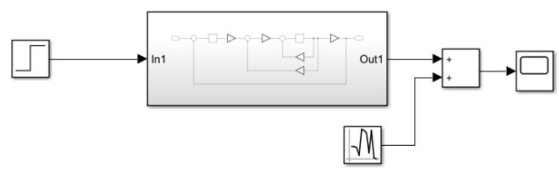


Figure 6. Block Diagram of Maxon EC-I 40 70 Watt DC Motor LQR with Noise
Image source: Author

2.7.4 LQT Block Diagram of Maxon EC-I 40 70 Watt DC Motor

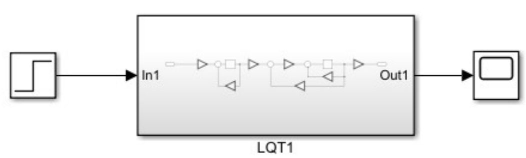


Figure 7. Block Diagram of LQT DC Motor Maxon EC-I 40 70 Watt. Image source: Author

2.7.5 Block Diagram of LQT DC Motor Maxon EC-I 40 70 Watt with Noise

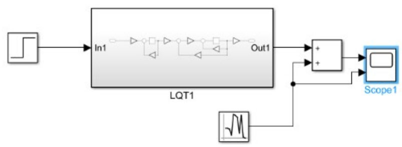


Figure 8. Block Diagram of Maxon EC-I 40 70 Watt DC Motor LQT with Noise

III.RESULTS & DISCUSSION

This section discusses the results of the response of the Maxon EC-I 40 70 Watt DC motor in the first order mathematical model and when the LQR and LQT methods are given with and without noise. The results were collected using simulations performed using Matlab Simulink software.

3.1. Second Order Response Results of Maxon EC-I 40 70 Watt DC Motor

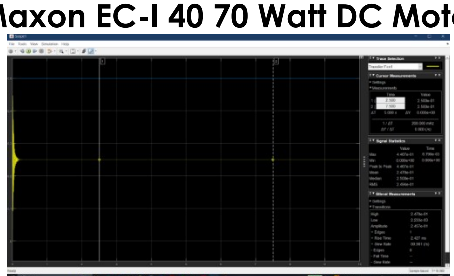


Figure 9. Response Results of Maxon EC-I 40 70 Watt DC Motor in Second Order Mathematical Modeling

In the output of figure 9 which describes the second-order modal response, it can be seen that the second-order motor response graph is far from the expected value. The yellow part is the result of the motor response, while the blue part is the expected value (set point) of 0.5. However, the motor response only reaches a value of 0.25 with a high level of fluctuation at the time the motor response rises. The observed Maxon EC-I 40 70 Watt DC motor shows linear characteristics with a smooth signal curve without fluctuation. The motor response reaches a steady state condition of around ±0.27 seconds.

3.2. Response Results of Maxon EC-I 40 70 Watt DC Motor Using LQR Method

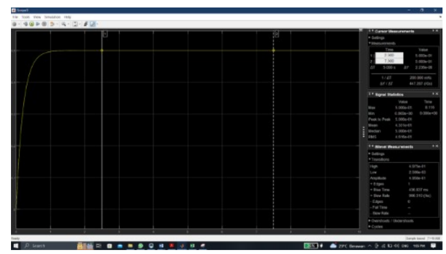


Figure 10. Response Results of Maxon EC-I 40 70 Watt DC Motor with LQR Method.

In Figure 10 which displays the results of the capital response, it can be seen that the motor response graph of the Maxon EC-I 40 70 Watt DC Motor controlled using the LQR method reaches a value that matches the desired set point. The desired set point value is 0.5, and the motor response successfully reaches that value in about ±1.2 seconds without overshoot or undershoot. As a result, the use of the LQR method makes the response of the Maxon EC-I 40 70 Watt DC motor better than if the LQR method was not used.

3.3. Comparison Results of Maxon EC-I 40 70 Watt DC Motor Response Using LQR Method and Without LQR Method

Figure 11. Comparison Results of Maxon EC-I 40 70 Watt DC Motor Response with LQR Method and Without LQR Method
Image source: Author

In the modal response comparison image in Figure 11, it can be seen that the response graph of the Maxon EC-I 40 70 Watt DC Motor shows a significant difference between using the LQR method and not using the method. The orange line is the desired set point value, the blue line is the motor response without the LQR method, and the yellow line is the motor response with the use of the LQR method. From Figure 11, it is clear that the response of the Maxon EC-I 40 70 Watt DC Motor using the LQR method produces better performance than that without using the LQR method. This response reaches a value that matches the desired set point without overshoot or undershoot.

3.4. Response Results of Maxon EC-I 40 70 Watt DC Motor Using LQR Method with Noise

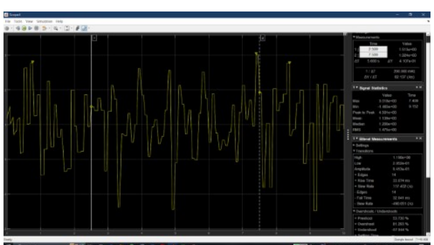


Figure 12. Response Results of Maxon EC-I 40 70Watt DC Motor with LQR Method When Given Noise

Figure 12 shows that the yellow signal, which is the response result of the Maxon EC-I 40 70 Watt DC motor using the LQR method, changes shape after being exposed to noise interference. The shape of the signal becomes very wavy with many fluctuations, and follows the pattern of the incoming noise signal. The resulting signal no longer has linear characteristics and is far from reaching a stable condition or steady state at the set point value that has been set.

3.5. Response Results of Maxon EC-I 40 70 Watt DC Motor Using LQT Method

Figure 13. Maxon EC-I 40 70Watt DC Motor Response Results with LQT Method

Figure 13 shows the modal response output of the Maxon EC-I 40 70 Watt DC motor using LQT. The output has the same output as the desired set point value of 0.5 and a very fast response time to steady state of 8,364 us. However, the resulting response has an overshoot of 4.7% and an undershoot of 0.8%.

3.6. Comparison Results of Maxon EC-I 40 70 Watt DC Motor Response Using LQT Method and Without LQT Method

Figure 14. Response Results of Maxon EC-I 40 70Watt DC Motor with LQT Method When Given Noise

Figure 14 shows that the yellow signal, which is the result of the response of the Maxon EC-I 40 70 Watt DC motor using the

LQT method, changes shape after being affected by noise interference. The signal becomes very turbulent with many fluctuations and imitates the pattern of the incoming noise signal. The resulting signal no longer shows linear characteristics and is far from reaching a stable condition or steady state at the set point value that has been set.

3.7. Response Results of Maxon EC-I 40 70 Watt DC Motor Using LQT Method with Noise

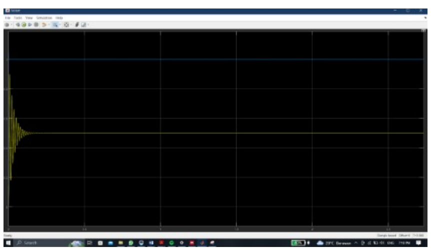


Figure 15. Motor Response Comparison ResultsDC Maxon EC-I 40 70 Watt with LQT Method and Not
Image source: Author

In the modal response comparison image in Figure 15, there is a significant difference between the motor response graph of the Maxon EC-I 40 70 Watt DC Motor using the LQT method and the one that does not. The orange waveform is the desired set point value, the blue waveform is the motor response without the LQT method, and the yellow waveform is the motor response with the use of the LQT method. From Figure 15, it is clear that the motor response of the Maxon EC-I 40 70 Watt DC Motor using the LQT method produces better performance than the one that does not use the LQT method.

IV.CONCLUSION

From the experiments conducted on the Maxon EC-I 40 70 Watt DC motor, it was found that the use of the LQR method produced a response that was in accordance with the desired set point value without overshoot and undershoot. The time required to reach steady state conditions was approximately ±1.2 seconds faster than not using the method. On the other hand, when the LQR method was not used, the motor response was far from the desired set point value, and reaching steady state conditions took quite a long time. The response results of the Maxon EC-I 40 70 Watt DC Motor with the use of the LQR method in situations with noise followed the pattern of the noise signal given to the system, so that the resulting response was affected by the disturbance.
The response of the Maxon EC-I 40 70 Watt DC motor is no longer linear. When the LQT method is applied to the motor, the time required to reach steady state conditions is very short, which is around 8,364 microseconds. However, the resulting response has an overshoot of 4.7% and an undershoot of 0.8%. The response results of the Maxon EC-I 40 70 Watt DC motor with the use of the LQT method in a situation with noise interference cause the response to follow the pattern of the noise signal given to the system, so that the resulting response is no longer linear. The LQT method is considered superior to the LQR method because it is able to produce a faster response in reaching the set point value on the Maxon EC-I 40 70 Watt DC motor.

V.CLOSING

1.Awards

research, especially those who funded your research. Include individuals who have helped you with your study: Advisors, Financial Supporters, or perhaps other supporters such as Proofreaders, Typists, and Suppliers who may have provided materials.

The researcher realizes that without the support of various parties, the compilation of this community service journal will never be realized. So on this occasion the researcher would like to express many thanks to the various parties who have participated. (This point can be adjusted again by adding words or including the party who wants to be appreciated)

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