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Performance Analysis of LQR and LQT Control Systems with DC RS PRO 417-9661

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ABSTRACT

Technology is intended to improve human work efficiency, but technology performance can be affected by various factors, including environmental factors, controller configuration with computers, and characteristics of the technology itself, often referred to as interference. This interference can result in the technology not operating optimally. Therefore, it is necessary to optimize the system to reduce interference. This research was carried out to evaluate the impact of interference on the system, using a DC motor model 417-9661 as a study object. DC motor systems are utilized in a variety of configurations involving various inputs and outputs. In this context, two variables are also introduced, namely order 1 and order 2. This research process involves the use of Matrix Laboratory (MATLAB) software and involves several stages. First, there is the mathematical modeling stage of the motor to obtain the first-order and second-order transfer function values. Second, a simulation is carried out on each configuration to be analyzed. Finally, a comparison of the signal output results from each configuration was carried out. The research results show that interference has a very high impact on the 417-9661 DC motor. Therefore, an optimization method is needed to reduce interference with the motor. Furthermore, second-order motorbikes show superior performance compared to first-order motorbikes, especially seen from the riding time conditions.

Key Word : Comparison, LQR, LQT, *Noise*, Optimization.

I.INTRODUCTION

Current technological developments are always in line with human progress, and as the quality of human resources increases, the available technology becomes increasingly sophisticated. In the process of increasing efficiency in completing various tasks, especially in the industrial sector, an efficient system is needed to speed up the production process [1].

In an industrial context, electronic equipment is often used, such as DC motors. DC motors act as devices that convert electrical energy into mechanical energy or movement [2]. It is important to note that a DC motor will only work optimally when it is supplied with voltage and direct current (DC) [3][4]. This research uses a DC motor type RS PRO 417-9661 with a voltage of 12 V. This DC motor is capable of reaching a maximum speed of around 47 rpm and produces a maximum torque of 157.02 mN.m at the highest efficiency conditions [5]. However, when a DC motor is operated with direct current, its performance does not reach the expected optimal level. Therefore, a control method is needed to improve the performance of this DC motor [6][7].

In an effort to optimize the performance of the RS PRO 417-9661 DC Motor, two different methods were used. The first method is Linear Quadratic Regulator (LQR). LQR aims to optimize the motor response to be closer to the set point value, and at the same time reduce undershoot and overshoot[10]. LQR has the characteristics of durability, reliability and static strengthening. When applied in complex systems with many inputs, LQR allows economical control of multiple outputs. This method was developed to design an optimal controller that minimizes a predetermined cost function [8][9].

The second method used is Linear Quadratic Tracker (LQT). LQT is a linear regulatory system where the system output follows the desired reference path [11]. The working mechanism of LQT involves a model-based tracking setup that uses state feedback to achieve optimal control. LQT involves the usual state feedback of a linear dynamic system along with additional feedforward control [12][13] LQT is usually used to solve optimization problems related to tracking [14][15]

This research aims to compare the output response of the 417-9661 type DC motor with two system optimization techniques, namely Linear Quadratic Regulation (LQR) and Linear Quadratic Tracker (LQT). In addition, the experiment will also include adding noise to each circuit to evaluate the impact of noise on both simulated methods. All of this research will be carried out using Matrix Laboratory (MATLAB) software to design the circuit and analyze the output response[16].

II.METHODOLOGY

1. Research Process

Based on the background that has been described, this research will follow a series of steps:

1. Literature Study

The first stage of the research involved a literature review. At this stage, references related to the optimization of linear quadratic regulators and linear quadratic tracking systems will be sought. This reference functions as a guide to resolve the problems faced. This reference source will be obtained from two main sources, namely scientific journals/articles and technical data sheets.

2. Mathematical Model Design

The next step is designing a mathematical model. This process involves theoretical calculations to produce order 1 and order 2 mathematical models based on the information contained in the technical data sheet. This mathematical model will be used as a transfer function in circuit simulation.

3. Creating a System Circuit

After designing the mathematical model, the next stage is to create various series of systems that will be simulated. This process will be carried out using MATLAB software. There are four types of circuits that will be created, namely LQT circuits, LQT circuits with additional noise, LQR circuits, and LQR circuits with additional noise.

4. System Output Response Analysis

At this stage, an analysis of the output response from the system circuit signal simulation is carried out. The main focus of this research analysis is to compare and contrast the two system optimization techniques used.

5. Conclusion

The final stage of this research is to draw conclusions based on the results of the analysis that has been carried out previously.

2. Mathematical Model of DC Motor RS PRO 417-9661

1. Datasheet DC Motor RS PRO 417-9661

RS PRO 417-9661 DC Motor Specifications:

Motor : Motor DC RS PRO 417-9661

: 0,465 N/m

Rated current : 0,99 A

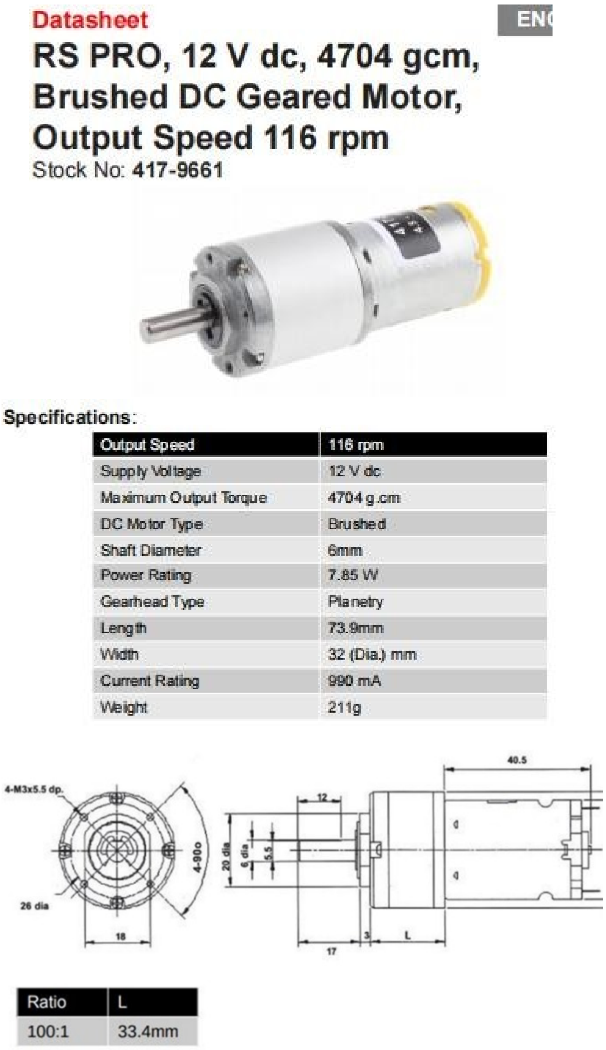
Voltage : 12 V

Speed : 116 rpm

Reduction Ratio : 1:100

Diameter : 32 mm

Radius motor : 16 mm = 0,016 m



Datasheet

EN

RS PRO, 12 V dc, 4704 gcm, Brushed DC Geared Motor, Output Speed 116 rpm

Stock No: **417-9661**

Specifications:

Output Speed	116 rpm
Supply Voltage	12 V dc
Maximum Output Torque	4704 g.cm
DC Motor Type	Brushed
Shaft Diameter	6mm
Power Rating	7.85 W
Gearhead Type	Planetry
Length	73.9mm
Width	32 (Dia.) mm
Current Rating	990 mA
Weight	211g

Ratio	L
100:1	33.4mm

Figure 2 *Datasheet DC Motor RS PRO 417-9661*

2. 1st Order Mathematical Modeling

The author can extract the mathematical model of the RS PRO 417-9661 DC motor system which corresponds to the first order model. A first-order system refers to a system with one major change. Following are the details of first order system modeling.

General equation of 1st order transfer function:

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

Based on the MY1016Z2 motorbike datasheet, we get a 1st order equation: Where τ= K.i so that the DC Motor 1st order equation becomes:

$$K=\frac{\tau}{i}=\frac{0{,}461}{0{,}99}=0{,}465 \qquad (2)$$

$$G(s)=\frac{0{,}465}{0{,}461\,s+1} \qquad (3)$$

3. 2nd Order Mathematical Modeling

The author can extract the mathematical model of the DC motor system RS PRO 417-9661 which corresponds to the second order model. Following are the details of the second order system modeling.

General form of second order transfer function

$$G(s)=\frac{\omega n^2}{s^2+2\,\omega ns+\omega n^2} \qquad (4)$$

To:

$$G(s)=\frac{2\,\pi F^2}{s^2+2\,c\omega\pi Fs+2\,\pi F^2} \qquad (5)$$

$$G(s)=\frac{98596}{s^2+62800\,s+98596} \qquad (6)$$

3. Optimal Control Linear Quadratic Regulator (LQR)

LQR is an optimal control method designed to direct the final state to zero by minimizing the cost function. This control method aims to find the value of the status feedback amplifier (K)[17]. Suppose a system (plant) has a representation in the form of state space as stated in Equation (1).

$$x=Ax+Bu \quad (7)$$

$$y=Cx \quad (8)$$

With the performance index in Equation (2)

$$J=\frac{1}{2}\int_0^\infty \square [x^T(t)Qx(t)+u^T(t)Ru(t)]dt \quad (9)$$

Where Q is a positive-definitive, positive-semi definitive, or symmetric real matrix, and R is a positive-definitive or symmetric real matrix. The matrices x* and u* are the results of the conjugate transposition of the matrices x and u. The conjugate transposition (often also called the adjoint matrix or Hermitian transposition) of a matrix is obtained by transposing the matrix and then conjugating each complex element in the matrix [18]. It should also be noted that in the equation, the second part on the right reflects the energy calculation of the resulting control signal. The weighting matrices Q and R indicate the relative importance of errors and energy expenditure in the system [19]. In this context, it is assumed that the control vector u(t) is not uncontrollable. If there are K matrix elements that can minimize the performance index, then u(t) = -Kx(t) will be the optimal solution for each initial state x(0). The block diagram for the LQR configuration can be seen in Figure 2.

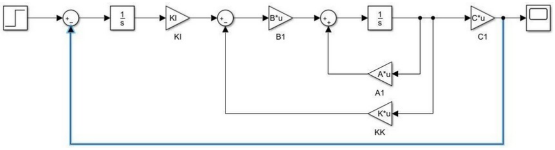


Figure 2. Block Diagram LQR

To get the value of the feedback state amplifier (K) using Matlab, you can use the syntax: "[K, S, E] = lqr(A, B, Q, R)," where S is the solution to the Riccati equation and E is the eigenvalue of closed loops. This regulatory problem can be solved by finding a solution to the Riccati equation as seen in the following equation

$$A^T P+PA-PBR^{-1}B^T P+Q=0 \quad (10)$$

Determining the value of the weighting matrices Q and R is based on the principle that the greater the value of the matrix Q, the greater the value of the reinforcing element K, which functions to speed up the system in reaching a steady state (intermediate state cost function). If the value of R is increased, the value of the amplifier K will decrease, resulting in the system reaching steady state (energy control) more slowly[20].

4. Program Matlab *Linear Quadratic Regulation* (LQR) in Motor DC RS PRO 417-9661

```
% OPTIMASI SISTEM LQR PADA MOTOR DC

clear; clc;

% Model Motor DC

J=0.0000012 ; b=0.1 ; K=0.0125 ; R=0,80 ; L =0.00015 ;

% J = Momeninesia , b = Rasioredam, K= konstanta, R= resistansi, L=

% Induktansi



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)];
```

5. Linear Quadratic Tracker (LQT) Optimal Control

In a tracking system, control system optimization aims to "push" the system output so that the resulting output is as expected. LQT (Linear Quadratic Tracking) involves standard state feedback of a linear dynamic system, as well as additional feedforward control concepts. The use of feedforward control depends on the reference signal vector, r(t), which is expressed as:

$r(t)=$¿ (11)

The LQT scheme focuses on minimizing the quadratic performance index in order to achieve control optimization decisions, which can be formulated in the form of the following equation:

$$e=z-y \tag{12}$$

$$J=\frac{1}{2}e'(tf)\,F(tf)\,e(tf)+\frac{1}{2}\int_{0}^{\infty}\square\left[x^{T}Qx+u^{T}Ru\right]dt \tag{7}$$

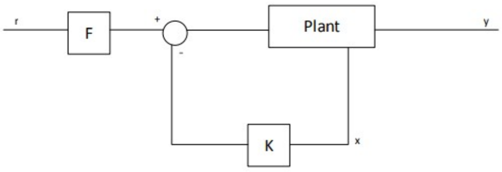


Figure 3. Block Diagram LQT

In this context, Q and R are weighting matrices for intermediate and control states. These two matrices are chosen with certain requirements, namely Q = QT ≥ 0 and R = RT > 0. Because the cost function has quadratic properties, the control signal is directly proportional to the squared variation of the equation.

6. Program Matlab *Linear Quadratic Tracker* (LQT) in Motor DC RS PRO 417-9661

```
clear clc


%parameter sistem MSD

m=2;

k=8;

b=6;

%Matriks pada state

A=[0 1;k/m -b/m];

B=[0;1/m];

C=[1 0];

%bobot

Q=[1 0;0 1]; R=10;

[S,eig,G] = care(A,B,G) %riccati 0=A'S+SA-
SB(inv R)B'S+Q Kx=inv(R)*B'*S %feedback
Gain Kx
```

```
Kr=(Kx*(inv(A))*B-eye(1))*(inv(C*(inv(A))*B)) Ahat=[0 1 0;-k/m -b/m 0;1 0 0] Bhat=[0;1/m;0]

%bobot hat

Qhat=[1 0 0;0 1 0;0 0 1];

Rhat=6;

[Shat,eighat,Ghat] = care(Ahat,Bhat,Qhat) %Riccati 0=A'S+SA-SB(inv R)B'S+Q

Khat=inv(Rhat)*Bhat'*Shat Kw=Khat(:,3)
```

7. Simulation Matlab

1. *RS PRO 417-9611 DC Motor First Order Circuit*

In the context of this research, a first-order circuit is used to observe the original output response of the RS PRO 417-9611 DC motor without any influence from optimization methods or noise interference.

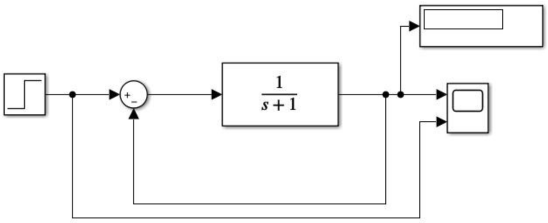


Figure 4. DC Motor First Order Circuit

Figure 4 shows a first order circuit for a DC motor. This circuit consists of one input and one output. The input uses a step signal type. The transfer function used in this circuit is a mathematical representation of the DC motor RS PRO 417-9611 which has first order. The output response results are displayed on the scope to monitor the response results that occur.

2. Linear Quadratic Regulation (LQR) Circuit for DC Motor RS PRO 417-9611

The RS PRO 417-9611 DC Motor Circuit which has been optimized using the Linear Quadratic Regulator (LQR) method is used to analyze the DC motor output response when the LQR method is implemented using Matlab Simulink software.

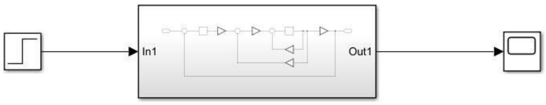


Figure 5. LQR Motor DC RS PRO 417-9661

3. Series of Linear Quadratic Regulation (LQR) DC Motor RS PRO 417- 9611 with Noise

The RS PRO 417-9611 DC Motor Series which has been improved with the Linear Quadratic Regulator (LQR) optimization method and added noise, is used to observe the output response of the DC motor when applying the LQR method and adding noise interference in the system. This process is carried out through Matlab Simulink software.

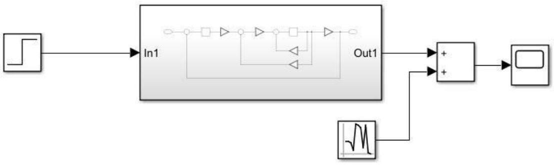


Figure 6. RS PRO 417-9661 DC Motor LQR Circuit with Noise

4. Linear Quadratic Tracker (LQT) Series DC Motor RS PRO 417-9611

The RS PRO 417-9611 DC Motor LQT circuit is used to determine the output response results of a DC motor if the DC motor is given the addition of the LQR optimization method which is carried out in Matlab Simulink.

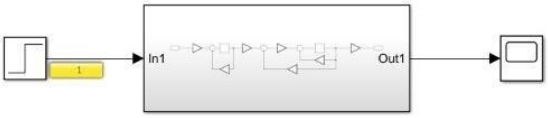


Figure 7. LQT DC Motor RS PRO 417-9661 circuit

5. Series of Linear Quadratic Tracker (LQT) DC Motor RS PRO 417-9611 with Noise

The RS PRO 417-9611 DC Motor Series which has been improved with the Linear Quadratic Tracker (LQT) optimization method and introduced with noise interference, is used to evaluate the output response of a DC motor when applying the LQT method and adding noise interference in the system. This process is carried out through Matlab Simulink software.

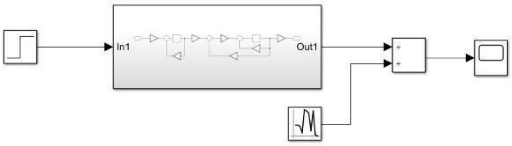
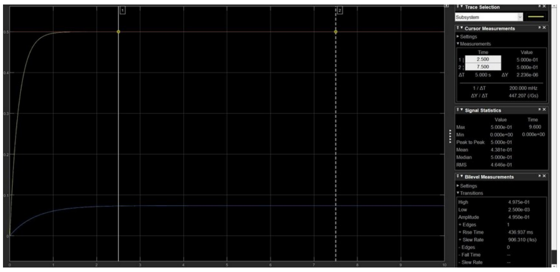


Figure 8. RS PRO 417-9661 DC Motor LQT Circuit with Noise

III. RESULT & DISCUSION

1. First Order Response Results for DC Motor RS PRO 417-9611



```
     Time          Value
1    2.500         5.000e-01
2    7.500         5.000e-01
ΔT   5.000 s   ΔY  2.236e-06
     1 / ΔT        200.000 mHz
     ΔY / ΔT       447.207 (/Gs)

               Value        Time
Max            5.000e-01    9.600
Min            0.000e+00    0.000e+00
Peak to Peak   5.000e-01
Mean           4.381e-01
Median         5.000e-01
RMS            4.646e-01

High           4.975e-01
Low            2.500e-03
Amplitude      4.950e-01
+ Edges        1
+ Rise Time    436.937 ms
+ Slew Rate    906.310 (/ks)
- Edges        0
- Fall Time    --
- Slew Rate    --
```

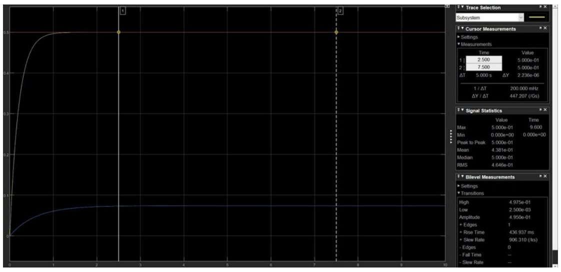
Figure 9. Comparison results of 37-GB500 DC motor response using the LQR method and not using the method

The first-order response output (as seen in Figure 9) displays the motor response in orange, while the blue line depicts the set point value fixed at 0.5. In this case, there is a significant difference between the set point value and the motor response which only reaches 0.07, so the distance between the two is quite large. The RS PRO 417-9611 DC motor has linear characteristics, which can be seen from the signal without any variations (ripple). The motor response reaches a steady state condition when it reaches the second second. However, it should be noted that the motor response in this case is relatively slow in the context of optimization.

2. RS PRO 417-9611 DC Motor Response Results using the LQR Method

The response output from the LQR circuit shows that the 37-GB500 motor response graph produces the same output as the targeted set point value, namely 0.5. The motor response reaches this set point at 1.2 seconds without any visible overshoot or undershoot phenomena. The response results of the RS PRO 417-9611 DC motor which was improved using the Linear Quadratic Regulation (LQR) method show better performance than the first order motor response.

3. Comparison Results of RS PRO 417-9611 DC Motor Response with LQR Method and Without Method



```
     Time          Value
1    2.500         5.000e-01
2    7.500         5.000e-01
ΔT   5.000 s   ΔY  2.236e-06
     1 / ΔT        200.000 mHz
     ΔY / ΔT       447.207 (/Gs)

               Value        Time
Max            5.000e-01    9.600
Min            0.000e+00    0.000e+00
Peak to Peak   5.000e-01
Mean           4.381e-01
Median         5.000e-01
RMS            4.646e-01

High           4.975e-01
Low            2.500e-03
Amplitude      4.950e-01
+ Edges        1
+ Rise Time    436.937 ms
+ Slew Rate    906.310 (/ks)
- Edges        0
- Fall Time    --
- Slew Rate    --
```

Figure 10. Comparison results of 37-GB500 DC motor response using the LQR method and not using the method

The comparison response output, as shown in Figure 10, between using the Linear Quadratic Regulator (LQR) method and without using this method produces a different graph. In this graph, the orange zone represents the desired set point value, the blue zone reflects the motor response without the LQR method being applied, while the yellow zone represents the motor response when the LQR method is used.

In Figure 10, it can be seen that the motor response applied using the LQR method has a more optimal response when compared to the motor response that does not use any method. Apart from matching the desired set point value, the motor response also reaches a stable state more quickly.

4. RS PRO 417-9611 DC Motor Response Results LQR Method with Noise

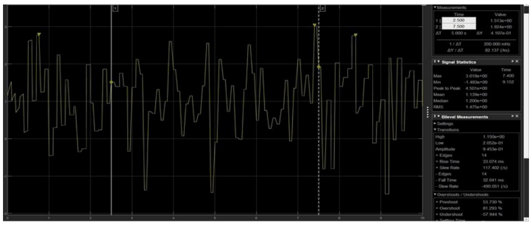


Figure 11. RS PRO 417-9661 DC Motor Response Results using the LQR Method when Noise is Given

In Figure 11, there are output response results from the LQR circuit which have been influenced by noise. It can be seen that the yellow signal undergoes a significant change in shape before the noise interference. The shape of the signal experiences many fluctuations which create shape changes similar to the introduced noise signal. As a result, the resulting signal no longer has linear characteristics and is far from reaching steady state conditions at a predetermined set point.

5. Hasil Respon Motor DC RS PRO 417-9611 dengan Metode LQT

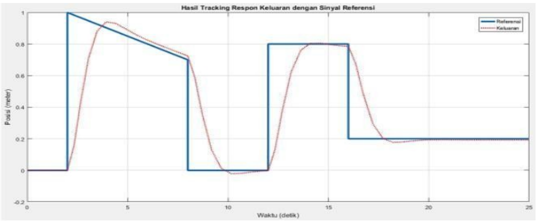


Figure 12. RS PRO 417-9661 DC Motor Response Results using the LQT Method

The Linear Quadratic Tracker (LQT) circuit response graph (seen in Figure 12) shows that the response of the 37-GB500 motor has output results that correspond to the targeted set point value, which is 0.5. The motor response managed to reach this set point at t=1.2 seconds without overshot or undershoot occurring. This shows that the response of the RS PRO 417-9611 DC motor which was improved using the Linear Quadratic Tracker (LQT) method has superior performance compared to the response of a first order motor.

6. RS PRO 417-9611 DC Motor Response Results with LQT Method and Without Method

Figure 13. Comparison results of the RS PRO 417-9661 DC motor response using the LQT method and not using the method

The output response comparison graph (see Figure 13) between the application of the Linear Quadratic Tracker (LQT) method and without the method shows a significant difference. In the graph, the orange zone represents the desired set point value, the blue zone depicts the motor response when the LQT method is not used, while the yellow zone depicts the motor response when the LQT method is applied. In the picture it can be seen that the motor response using the Linear Quadratic Regulator (LQR) method produces an optimal response compared to conditions without any method. Apart from achieving a response that corresponds to the set point value, the motor response also reaches a steady state more quickly.

7. RS PRO 417-9611 DC Motor Response Results LQT Method with Noise

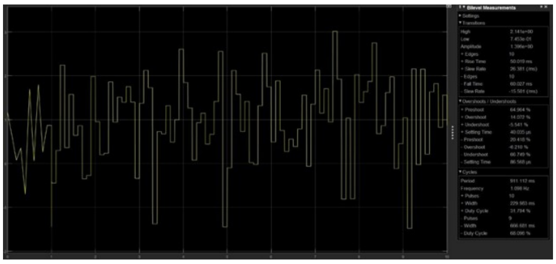


Figure 14. RS PRO 417-9661 DC Motor Response Results using the LQT Method when Noise is Given

In Figure 14, it can be seen that the output response of the LQT circuit with noise interference experiences a significant change in shape. The yellow signal experiences significant fluctuations before the noise. These fluctuations cause a lot of oscillations and cause a signal shape similar to noise interference. The impact of this disturbance results in the output signal no longer having linear characteristics, and is far from reaching steady state conditions at the set point value that has been set.

IV.CONCLUSION

Based on the simulation results of the RS PRO 417-9611 DC motor in various circuit configurations, two techniques were applied, namely Linear Quadratic Regulation (LQR) and Linear Quadratic Tracker (LQT), to improve the motor response. There are significant differences in the output signal in each circuit using the LQR, LQT, and first order models. However, it is important to note that adding noise to a circuit can result in quite large variations in signal response.

Therefore, in the comparative analysis of signal output results carried out, the research focused on the evaluation of linear quadratic regulation and linear quadratic tracking methods only.

V. REFERENCE

1. Acknowledgement

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