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Optimization of Dynamometer Braking Performance with LQR-PID Hybrid Control Method Approach on Eddy Current System

Jatmiko Adi Wijaya

Marine Electrical Engineering, Shipbuilding Institute of Polytechnic Surabaya, ITS Sukolilo, JL.Teknik Kimia, Keputih, Kec.Sukolilo, Surabaya City, East Java 60111
jatmikoadi20@student.ppns.ac.id

Abstract

This paper discusses the optimization of braking performance in the Eddy Current Brakes dynamometer system with the Linear Quadratic Regulator (LQR)-PID hybrid control strategy approach. The eddy current braking system is a modern technology that requires optimal control strategies to improve stability, efficiency, and braking accuracy. Although PID controls are widely used due to their simplicity and reliability, their performance is often considered less than optimal in certain scenarios, especially in the face of complex dynamic changes. Therefore, this study proposes to integrate the full-state feedback control of the Linear Quadratic Regulator (LQR) with PID to improve the overall braking performance. The simulation was conducted using MATLAB/Simulink software, focusing on a comparative analysis between conventional PID control methods and LQR control approaches. The simulation results show the advantages of LQR over PID, especially in terms of response time and overshoot elimination. LQR control results in a settling time (Ts) of 2.12 seconds and a rise time (Tr) of 1.18 seconds without overshoot, indicating higher stability. On the other hand, PID control provides a faster settling time (Ts) of 0.27 seconds, and a rise time (Tr) of 0.18 seconds, but there is still an overshoot of 0.7%, which has the potential to reduce braking efficiency in real systems. This research contributes to improving braking efficiency and offers a more stable solution for the Eddy Current system.

Keywords: Eddy current brakes, PID, LQR, MATLAB, hybrid control.

1. Introduction

The development of the automotive sector, especially in Indonesia, has made significant progress in recent decades, especially in terms of vehicle engine technology. In the automotive industry, each engine has different characteristics and performance, such as power, torque, and emission efficiency. Therefore, dynamometers are used to measure and analyze the performance characteristics of the engine in more detail. This tool can be used to evaluate the quality and performance of the machine, assist in design improvements, and ensure that the machine meets the desired performance and efficiency standards.

In this context, the Eddy Current Brakes Dynamometer system was chosen for its ability to provide rapid load changes, stable braking at high speeds, as well as easy-to-control acceleration. Compared to inertial dynamometers, Eddy Current Brakes offer greater flexibility and are more ideal for engine performance testing. The system utilizes the change in magnetic flux in the conductor disc that generates braking force at the time of engine performance testing, allowing analysis of timing parameters, braking force, and system stability (Nunes & Brojo, 2020).

However, to obtain optimal braking performance, a proper control system is required. PID controls that are still commonly used in industry are often not optimal enough in some situations. Therefore, a more modern and efficient control approach is needed. One solution that can be adopted is the use of a Linear Quadratic Regulator (LQR), a full state feedback-based controller that can theoretically provide a better response compared to PID control, especially in complex dynamic systems such as the Eddy Current Brakes Dynamometer (Houari et al., 2020).

Several previous studies have shown that LQR-based controllers can improve system performance in terms of response time and overshoot compared to PID. For example, research by Houari et al. (2020) in tilt-rotor aircraft control shows that LQR controllers can provide better results in terms of response time and reduce overshoot, a very important advantage in braking applications. Therefore, the application of LQR in the Eddy Current Brakes Dinamometer system is an attractive choice to optimize braking performance.

This paper aims to test and compare the performance between PID and LQR controls in the Eddy Current Brakes Dynamometer system. Simulations were conducted using MATLAB and Simulink to analyze the response time and stability of the system on each control approach. The results of this study are expected to

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contribute to the development of a more optimal and applicable control design for the Eddy Current Brakes system.

2. Material and methods

2.1. Material

The Eddy Current Brakes (ECB) braking system utilizes electromechanical components that work on the principle of magnetic field interaction with moving conductors. This system is known as modern braking technology which has advantages over traditional mechanical systems. The ECB provides a more responsive braking speed at high speeds and does not involve mechanical components that require intensive maintenance, thereby increasing durability and operational efficiency. According to Gulbahce et al. (2013), the main advantages of this system are the reduction in maintenance requirements and increased control over braking speed, which makes it ideal for dynamometer applications. Brin (2013) added that the ECB is easy to control with different types of controllers, which allows flexibility in different technical applications, such as testing engine performance on dynamometers.

The structure of the ECB model consists of several main components, including a rotating disc of conductors and coils that are passed through a current or permanent magnet to create a magnetic field. This model, as described by Chen et al. (2019), is divided into four parts: (1) the drive core and coil, (2) the airless gap, (3) the iron disc, and (4) the outer side of the iron disc, each of which has an important role in the braking process. This system allows for precisely controlled changes in braking force, which is essential for applications such as dynamometers.

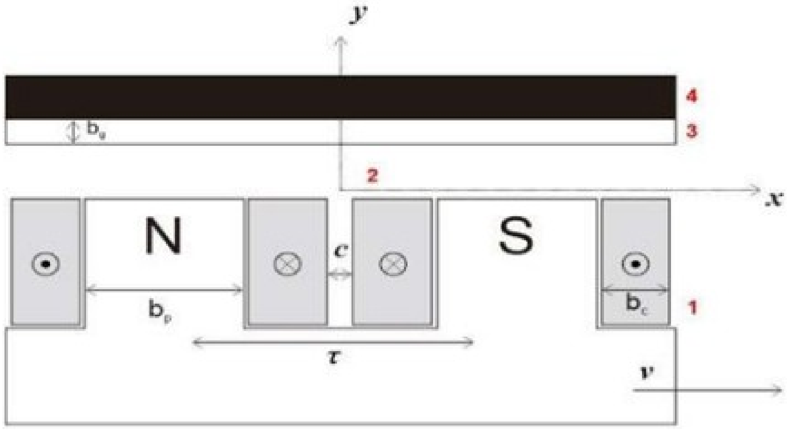

Figure 1. Two-Dimensional Model of the Eddy Current Brakes System

2.1.1 Eddy Current Brakes System Design and Modeling Scheme

The ECB dynamometer system works on the basic principle that the iron disc connected to the engine shaft rotates and is given a braking force. The braking force generated by the magnetic field in this system can be detected through the Load Cell sensor, which converts the force into an analog signal to be later processed by the microcontroller. This process allows real-time analysis and control of braking forces. As explained by Nahari et al. (2012), the Eddy Current generated by the change in magnetic flux on the iron disc triggers the braking force according to Lenz's law principle, which produces a braking force that is inversely proportional to the change in magnetic flux.

$$F=\int_{g}^{g+e} dz \int_{0}^{2} d\varnothing \int_{Rinner}^{Routter} \Delta F \varnothing \, rdr \qquad (1)$$

The rotational speed of the iron disc has a significant effect on the braking force generated by the ECB system. At low speeds, the braking force produced by the Eddy Current is quite small, but it increases at medium and high speeds. At high speeds, greater magnetic induction will reduce the effect of the initial braking force, which requires further adjustment to ensure system stability. In this study, the determination of the total braking force on the ECB is based on equation 1 which relates various parameters such as electromagnetic diameter, disc thickness, magnetic induction, and angular velocity (Chen et al., 2019).

Table 1. Eddy Current Brakes System Design Parameters

Parameters	Value
Disc thickness (d)	1 cm
Angular velocity (ω)	3000 RPM
Disc and pole spacing (x)	0.5 m

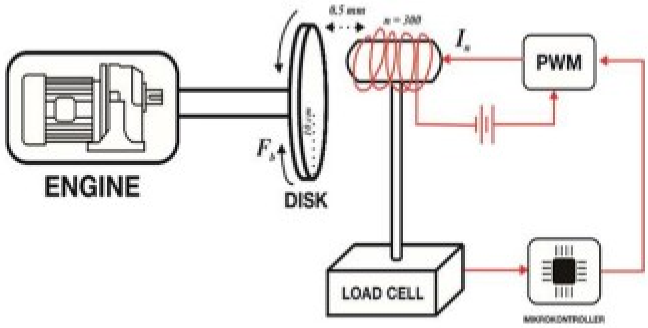

Figure 2. Eddy Current Brakes Dynamometer Design Scheme

To model this system, a state space and switch function approach is used, which allows for a more detailed analysis of the system. Through open loop analysis, the transient characteristics of the system response can be studied to gain an understanding of the stability of the system before the control design is carried out using the PID or Linear Quadratic Regulator (LQR) approach. Open loop modeling in the form of state space can be seen in Figure 3, which shows the Simulink block of the Eddy Current Brakes Dynamometer system.

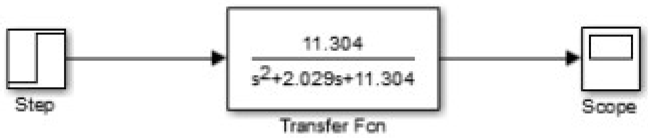

Figure 3. Simulink Block Eddy Current Brakes System Open Loop Dynamometer

The ECB system control approach is carried out with two main types of control, namely PID and LQR, which aims to compare the performance of both in optimally regulating braking force. PID control has proven to be effective in many engineering applications, but in more complex dynamic systems such as ECBs, LQR control based on full state feedback can offer better performance in terms of response time and system stability. According to a study by Houari et al. (2020), the use of LQR can provide more optimal results in controlling systems with more complex dynamics.

Figure 3 shows the ECB system block diagram in the form of an open loop used to analyze the system response before applying PID and LQR controls. The purpose of this study is to analyze the comparison between the two types of controls and determine which control is more effective in improving braking performance on the Eddy Current Brakes Dynamometer.

2.2 Methods

Eddy Current Brakes (ECB) braking systems have been the focus of research to improve braking system performance in a wide range of applications. Once the characteristics of the system in the open-loop condition are identified, the design of the control system becomes a critical step to optimize the system response, both through Proportional-Integral-Derivative (PID) and Linear Quadratic Regulator (LQR) controls. The implementation of the LQR-PID hybrid approach aims to integrate the advantages of each method to overcome the weakness of a single control in the Eddy Current Brakes system.

After the analysis of the characteristics of the open-loop system is obtained, the next step is to design a PID and LQR-based control strategy. This approach refers to a review of the literature and modern control theory as the basis for the control design applied to the Eddy Current Brakes Dynamometer system using the

MATLAB/Simulink simulation platform. The following is a detailed description of each control component used.

2.2.1 Proportional-Integral-Derivative (PID) Control

PID control is a classic approach widely used in single input single output (SISO) systems. This control works by comparing the error value (the difference between the setpoint and the actual output) to generate a control signal using proportional (Kp), integral (Ki), and derivative (Kd) parameters. According to Nugraha & Setiawan (2020), PID control is very effective in regulating braking systems because it is able to regulate the system's transient response, but often faces limitations in overcoming steady-state error fluctuations. PID control is conventionally divided into two types, namely dependent in Equation (2) and independent in Equation (3).

$$u(t) = K_p\left[e(t) + \frac{1}{\tau_i}\int e(t)dt + \tau_d \frac{d}{dt}e(t)\right] \quad (2)$$

$$u(t) = \left[K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt}e(t)\right] \quad (3)$$

$$K_a = \begin{bmatrix}0 & 0 & \dots & 0 & 1\end{bmatrix}\begin{bmatrix}B \\ AB \\ \dots \\ A^{n-1}B\end{bmatrix}\phi(A) \quad (4)$$

The PID constant tuning method in this study adapts the Ackermann pole placement formula shown in equation 4 to achieve system stability. Simulations on MATLAB/Simulink software produce a representation of the PID control with a block diagram that allows adjustment of the Kp, Ki, and Kd parameters to minimize steady-state errors, as demonstrated by Smith et al. (2019).

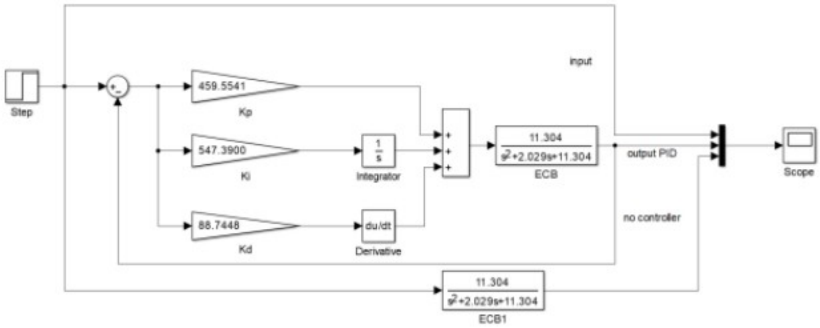

Figure 4. Simulink Block Eddy Current Brakes Dynamometer System with PID Control

2.2.2 Linear Control Quadratic Regulator (LQR)

As a complement, LQR control is used to optimize system performance based on state-space representations. LQR not only moves the system pole to the desired position but also considers the energy efficiency of the system, as explained by Houari et al. (2020). This approach addresses the drawbacks of traditional pole placement that often ignores the energy consumption of actuators, as revealed by Zhang & Wu (2020).

LQR design is carried out by determining the Q and R matrices that regulate the trade-off between system performance and actuator effort. An augmented system simulation that includes a gain reference input (Nbar) is used to achieve a zero steady-state error condition, shown in Figure 5. This is in line with the research of Lee et al. (2017), which showed that the arrangement of the Q and R matrices contributes directly to the efficiency of the actuator as well as the stability of the system.

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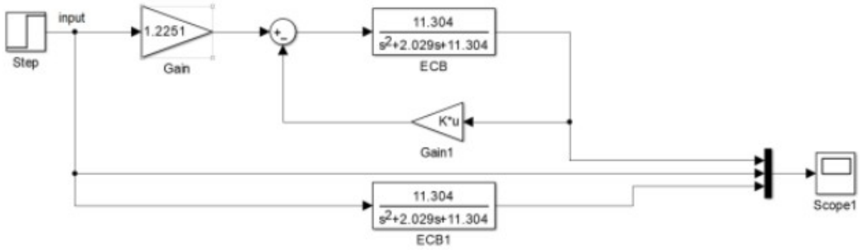

Figure 5. Simulink Block Eddy Current Brakes Dynamometer System with LQR Control

2.2.3 Zero Steady-State Error Design

While LQR controls produce good transient responses, there are steady-state error issues that need to be fixed. To achieve zero steady-state error, a gain reference input (Nbar) approach is used that ensures there is no difference between the reference input (setpoint) and the system output at a stable state. The calculation of N gain is carried out based on Equation (5)-(8), which is then implemented in the system simulation using MATLAB.

$$\begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (5)$$

$$u = -Kx + \left(N_u + KN_x\right) r \quad (6)$$

$$u = -Kx - \bar{N}r \quad (7)$$

$$\bar{N} = N_u + KN_x \quad (8)$$

2.2.4 LQR-PID Hybrid Approach

The integration of PID and LQR controls in a hybrid approach is designed to take advantage of the advantages of each method. PID control is used to ensure fast and accurate transient response, while LQR plays a role in optimizing the energy efficiency of the system and reducing steady-state errors. According to Gupta et al. (2020), this kind of hybrid strategy can produce a braking system with superior performance compared to a single-control approach.

3. Results and discussion

The simulation of the control system for Eddy Current Brakes on the dynamometer was carried out using MATLAB/Simulink software. The purpose of this simulation is to evaluate the performance of the system in meeting the specified response criteria, namely:

- Maximum overshoot value ≤ 10%.
- Settling time (Ts) ≤ 5 seconds.
- Rise time (Tr) ≤ 4 seconds.
- Zero steady-state error.

The simulation involves analyzing the uncontrolled system, the implementation of a PID controller, and an LQR controller, and comparing the performance of the two to determine the optimal approach.

3.1. Controllerless System Testing

The open-loop system test is carried out by providing input in the form of a step signal of 5 N. The simulation results, as shown in Figure 6, show the response of the system that undergoes an overshoot with a maximum braking force value of 6.85 N. Transient analysis of the system shows:

- Settling time (Ts) = 3.34 seconds.
- Rise time (Tr) = 0.394 seconds.
- Overshoot = 36.9% (1.85 N).

Although the settling time and rise time values are quite good, the high overshoot indicates that the system needs a controller to reduce those values to fit the design criteria.

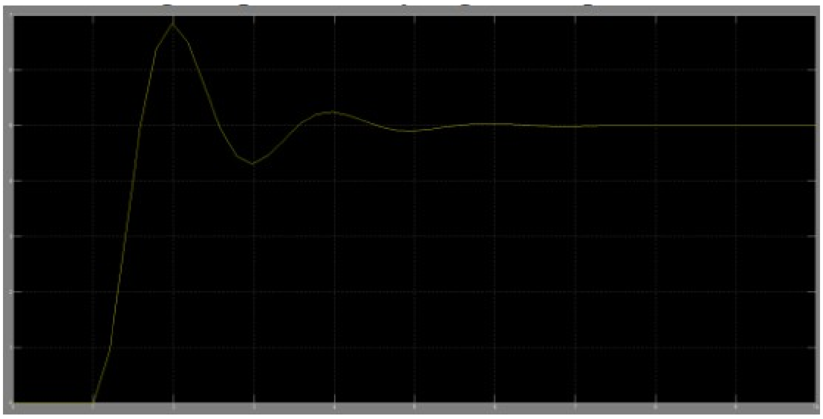

Figure 6. Open Loop System Test Results

3.2. Eigen-Value Analysis and Pole-Zero Map

The response of an open-loop system that has an overshoot is further analyzed using the eigenvalue approach. Based on the state-space calculation, the system eigenvalue is at:

$$\lambda = \begin{bmatrix} -1.0145+3.2054\,i & 0 \\ 0 & -1.0145-3.2054\,i \end{bmatrix} \tag{9}$$

The system pole is in negative territory, indicating that the system is intrinsically stable. However, to meet the design criteria, additional controls are required to minimize overshoot.

3.3. PID Controller Test Results

The PID controller is designed using the Ackermann Pole Placement approach by adding one dominant pole in the left position to create a stable augmented system. The operator parameters are obtained as:

- Kp=459.5541,
- Ki=547.3900
- Kd=88.7448.

Simulations using MATLAB/Simulink produce a PID-controlled system response as shown in Figure 7. The results of the analysis showed:

- Settling time (Ts) = 0.27 seconds (practically unrealistic).
- Rise time (Tr) = 0.18 seconds.
- Overshoot = 0.7%.

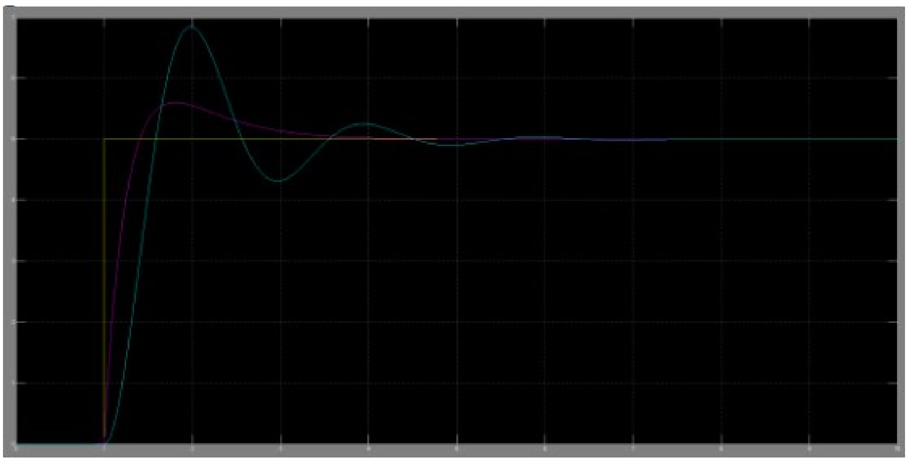

Figure 7. Test Results of System with PID Controller

The PID controller delivers stable system performance, despite an increase in gain of up to 5.7 N in less than 1 second. However, this approach still needs to be compared to LQR controls to identify optimal strategies.

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3.4. LQR Controller Test Results

The design of the Linear Quadratic Regulator (LQR) control begins by examining the controllability of the system using a controllability matrix. The system is declared fully controllable because the matrix rank value is the same as the system order. The Q and R matrices are set to optimize system performance:

$$Q=\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}, R=1 \qquad (10)$$

In the first test, the gain value was obtained as:

- K= [0.8025,0.3181],
- Gain reference input=1.2251.

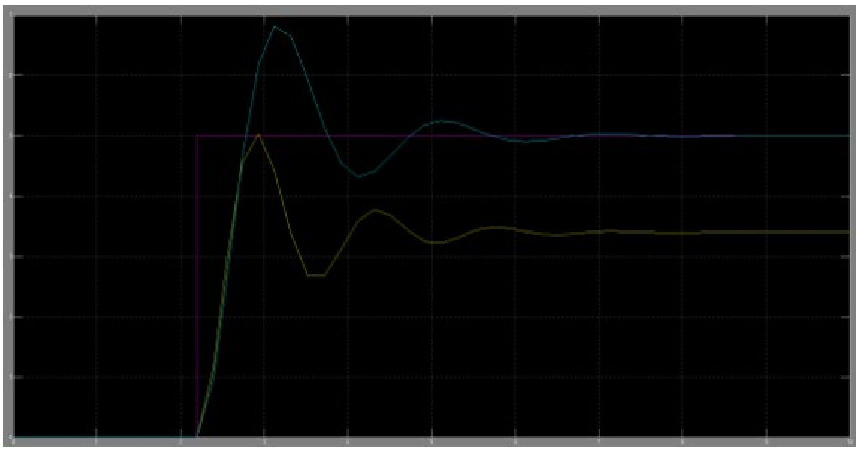

Figure 8. First Test Results using LQR Controller

The test results showed the values of settling time (Ts) = 2.19 seconds, rise time (Tr) = 1.18 seconds, and overshoot = 0%. The second test was conducted by modifying Q and R to improve the system response, yielding:

- K= [2.7815,0.0117],
- Gain reference input=1.0083.

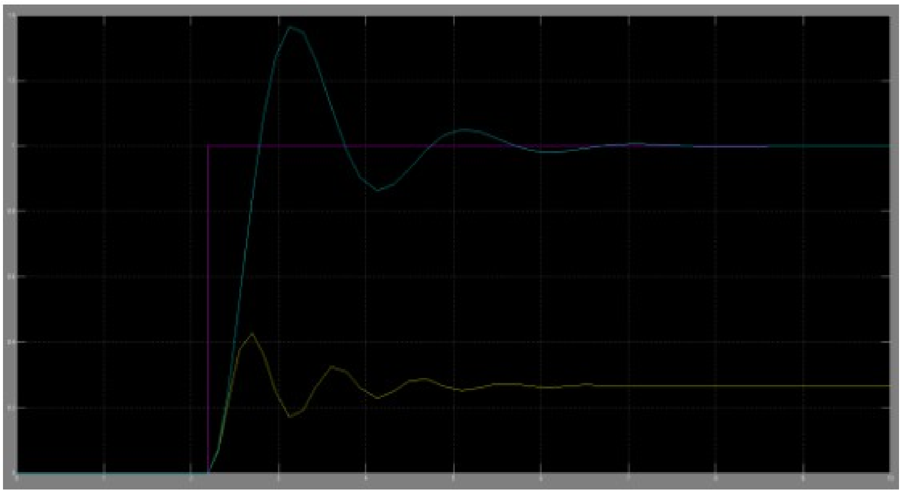

Figure 9. Second Test Results using LQR Controller

The second test result as shown in Figure 9 shows a significant increase with the value of settling time (Ts) = 2.12 seconds, rise time (Tr) = 1.18 seconds, and zero steady-state error.

3.5. Comparison of PID and LQR Controller Responses

The following table summarizes the performance comparison of the system with PID and LQR controllers:

Table 2. Comparison of PID and LQR Controller Responses

Criterion	PID	LQR
Settling time (Ts)	0,27 s	2.12 s
Rise time (Tr)	0,18 s	1.18 s
Overshoot (%)	0,7	0
Steady-state error	0	0
Braking force (N)	5 N	5 N

The use of LQR control has proven to be more optimal than PID. LQR provides flexibility in system performance settings using Q and R matrices, allowing for more precise adjustments to system dynamics and actuator efficiency. This conclusion is relevant to the findings of reviewers and editors to increase scientific contributions in the development of hybrid control strategies in engineering applications.

4. Conclusion

The Eddy Current braking system using PID control shows a fast transient response with a settling time (Ts) of 0.27 seconds, a rise time (Tr) of 0.18 seconds, and an overshoot of 0.7%. However, the response is not entirely optimal for implementation on the Eddy Current braking system. This is due to the high energy consumption required to maintain the stability of the braking force in a very fast time. If applied to hardware, this excessively short braking time response can reduce the overall efficiency of the system. In addition, PID control with Kp, Ki, and Kd parameters has a disadvantage in managing the dynamics of state variables thoroughly, which is necessary to ensure optimal performance in braking systems. In contrast, the Linear Quadratic Regulator (LQR) full-state feedback control approach offers a more efficient and optimal solution. In this study, the system with LQR control produced a settling time (Ts) value of 2.12 seconds and a rise time (Tr) of 0.18 seconds, without overshoot. A delay in braking time of 2 seconds allows for a significant reduction in energy consumption, making LQR control a more energy-efficient method for the Eddy Current braking system. Thus, LQR can overcome the limitations of PID control, especially in maintaining stability and energy efficiency in various system dynamics. The advantages of LQR control that are able to meet the design criteria of modern systems make it a superior alternative to classic PID control. The use of LQR is also relevant for further development in Eddy Current system control, especially in applications that prioritize energy efficiency and braking force stability. Therefore, the results of this study make a significant contribution to the development of hybrid control strategies, such as LQR-PID integration, which can combine PID response speed with LQR efficiency and stability.

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