Application of LQR-PID Control in Eddy Current Brake Dynamometer Systems for Community Skill Development

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Abstract: *This paper presents a comparative analysis of classical PID control techniques and modern control approaches in the Eddy Current Brake Dynamometer system. Eddy Current Brakes, as modern braking systems, require efficient control mechanisms to enhance their performance. Traditionally, PID control has been widely employed; however, it is often deemed suboptimal in certain scenarios. To address these limitations, this study explores the development of a more modern and optimal control system utilizing Full-State Feedback Linear Quadratic Regulator (LQR). The comparative analysis of braking response times was simulated using MATLAB/Simulink. Results demonstrate that LQR control outperforms PID control in terms of braking response, with a settling time (Ts) of 2.12 seconds, a rise time (Tr) of 1.18 seconds, and zero overshoot. Conversely, while PID control achieves faster Ts (0.27 seconds) and Tr (0.18 seconds), it exhibits an overshoot of 0.7%, which may impact system stability. Furthermore, this research underscores the potential of integrating LQR-based control systems into community-oriented technical training programs. The improved performance metrics of the LQR control can enhance the practical learning experience, particularly in vocational education aimed at equipping underserved communities with advanced technical skills. By leveraging these findings, the study highlights the importance of adopting innovative control strategies to bridge the gap between theoretical knowledge and practical application, contributing to sustainable skill development initiatives.*

Keyword: *Eddy brakes, PID, LQR, Matlab*

Introduction

The automotive sector, particularly in Indonesia, has experienced significant growth over the past decades, especially in the area of vehicle engine technology. In the automotive industry, each engine possesses unique characteristics and capabilities, including engine power, torque, and fuel emissions. To analyze these characteristics comprehensively, a dynamometer is employed as a critical tool to evaluate engine performance. This equipment enables deeper analysis of engine performance parameters, providing essential data for further optimization.

To ensure optimal braking performance in dynamometer systems, Eddy Current Brake Dynamometers have been adopted. These systems are preferred for their ability to deliver rapid load changes, excellent braking performance at high speeds, stable conditions, and easily controllable acceleration. This makes Eddy Current Brake Dynamometers highly flexible and ideal for engine performance testing compared to inertia dynamometers [14]. The system operates by utilizing the currents generated by magnetic flux changes in the conductor disc to produce braking force, which is critical for engine performance testing [5]. Key parameters analyzed include braking time, braking force, and system stability during braking, all aimed at achieving optimal performance.

To achieve the desired braking response performance, an optimal control system design is required[16]. While classical PID control remains widely used in industrial settings, it is often suboptimal for controlling complex plants like Eddy Current Brake Dynamometers. Studies on PID control optimization frequently focus on fine-tuning control parameters [1][17]. However, to develop an optimal control system, a full-state feedback controller, such as Linear Quadratic Regulator (LQR), can be utilized.

In several scenarios, full-state feedback controllers demonstrate superior performance compared to PID controllers [20]. For instance, a comparative study by Houari et al [18][19] on tilt rotor airplane control revealed that LQR yielded better results in terms of overshoot and response time criteria. Thus, adopting LQR for Eddy Current Brake Dynamometers represents a promising direction for modernizing control system designs and achieving optimal braking response times.

This paper explores the simulation of control design for Eddy Current Brake Dynamometer systems using the LQR control method. Simulations were conducted using MATLAB software, with the system modeled in state-space representation. System responses, with and without controllers, were observed using MATLAB Simulink features. The comparative analysis focuses on braking response performance, contrasting classical PID control with optimal LQR control.

The objective is to demonstrate that LQR control provides superior and more optimal braking response performance compared to PID control in Eddy Current Brake Dynamometers.

Methodology

1. Eddy current breaks

Eddy Current Brakes, which utilize electromechanical components, represent a more modern braking system compared to conventional mechanical braking systems [7]. The Eddy Current Brake Dynamometer system offers several advantages, including highly responsive braking at high speeds, enhanced durability due to the absence of mechanical components that require extensive maintenance, and ease of control using various control strategies [3]. These characteristics make the Eddy Current Brake Dynamometer a reliable and efficient choice for applications requiring precision and durability.

The structure of the Eddy Current Brake system consists of a rotating conductor disc and a coil, which is energized by electric current or equipped with permanent magnets to generate a magnetic field over the conductor disc [4]. This interaction between the magnetic field and the conductor disc creates the braking force necessary for operation.

Based on its structural components, Eddy Current Brakes are divided into four main parts, as illustrated in Figure 1:

1. Core and Exciting Coil: The core serves as the foundation for generating the magnetic field, with the exciting coil providing the necessary current to create a variable magnetic flux.

2. Air Gap: The air gap ensures minimal resistance while maintaining effective magnetic interaction between the coil and the conductor disc.
3. Conductor Disc: The rotating disc serves as the medium for magnetic flux interaction, inducing eddy currents that produce braking force.
4. Outer Edge of the Conductor Disc: This part interacts directly with the magnetic field, ensuring optimal performance and efficient energy dissipation.

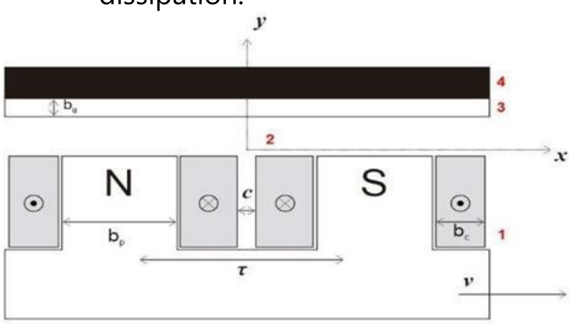

Figure 1. 2d model of eddy current brakes system

Annotations:
(a) Core and Exciting Coil
(b) Air Gap
(c) Conductor Disc
(d) Outer Edge of the Conductor Disc

The adoption of Eddy Current Brakes in dynamometer systems aligns with community development initiatives by introducing modern technological solutions that are both efficient and sustainable. Training programs can leverage this technology to enhance vocational skills in precision engineering and electromechanical system maintenance. These programs contribute to empowering local communities with high-demand skills, creating opportunities for employment in industries where advanced braking systems are used.

The operational mechanism of the Eddy Current Brake Dynamometer involves a rotating iron disc, which is connected to the shaft of a machine. When a braking force input is applied, the system detects the magnitude of the braking force through a load cell sensor. This sensor plays a critical role by converting the magnitude of the braking force into an analog signal. The analog signal is then processed as a variable input by a microcontroller. The feedback from the load cell enables the microcontroller to analyze the stability of the braking response within the system.

Eddy currents, which are induced due to changes in the magnetic flux within a conductor, are integral to the functionality of the Eddy Current Brake Dynamometer [13][10]. In this system, the conductor is an iron disc with a diameter of 10 cm, integrated with the machine's shaft (dynamo). According to Lenz's Law, Eddy currents generate a magnetic field that opposes the change in the magnetic field that caused their induction. This phenomenon is harnessed to create a braking force (denoted as Fb) in the dynamometer. The force Fb arises due to the interaction between the magnetic field vector and the Eddy currents.

Performance Across Different Speeds

1. Low-Speed Conditions: At low rotational speeds, the magnetic induction in the iron disc causes minimal Eddy currents, which can be considered negligible due to the magnetic induction being nearly perpendicular to the disc surface.

2. Medium-Speed Conditions: At medium speeds, a greater braking force is generated as compared to low speeds. The magnetic induction at the poles becomes less than the initial magnetic induction (B0B_0B0).
3. High-Speed Conditions: At high speeds, the magnetic induction at the poles due to Eddy currents exceeds B0B_0B0. Consequently, the initial magnetic induction becomes negligible.

The design schematic of the Eddy Current Brake system is presented in Figure 2, and the relevant parameters are outlined in Table 1. Based on the system modeling, the total braking force generated by the Eddy Current Brake is mathematically formulated as shown in the given equation.

$$F= \int_{g}^{g+e} dz \int_{0}^{2} d\emptyset \int_{Rinner}^{Routter} \Delta F \emptyset r dr \quad (1)$$

Table 1. system eddy current breaks parameter

Parameter	value
Thickness of disk *(d)*	**1 cm**
Speed of eagle *(ω)*	**3000 RPM**
Disk and pole distance *(x)*	**0.5 m**

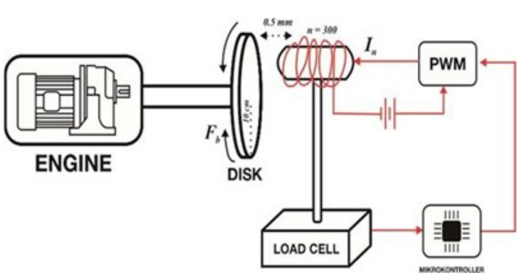

Figure 2. Design and scheme eddy current brakes dynamometer

Equations (2) and (3) are the results of solving the total braking force equation for eddy current brakes. Where F is braking force (N), D is electromagnetic pole diameter (m), d is disk thickness (cm), B is magnetic induction (Tesla), c is proportional factor, ω is angular speed (RPM), x is distance disk and pole (m) and R is disk radius (m).

$$F = 0.25\frac{\pi}{4}D^2 d B^2 c\omega \quad (2)$$

$$c = 0.5\left[1-\frac{0.25}{\left(1+\frac{\pi}{R}\right)^2\left(\frac{R-x}{D}\right)^2}\right] \quad (3)$$

From all specifications, a similar relationship can be found between current (I) and braking force represented in the form of state space and transfer function based on the reduction from Equations (2)-(3) to Equation (5) for modeling the state space and transfer function in Equation (6).

$$I = 2.106 \ln(F) + 5.288 \quad (4)$$

$$\dot{x}(t) = \begin{bmatrix}-2.029 & -2.826\\ 4 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix}+\begin{bmatrix}2\\ 0\end{bmatrix}u(t); \quad y=\begin{bmatrix}0 & 1.413\end{bmatrix}x(t) \quad (5)$$

$$G_{(s)} = \frac{11.304}{s^2+2.029s+11.304} \quad (6)$$

Through modeling using state space and transfer functions, the force system response can be analyzed using PID or LQR. The open loop model in state space form of the Eddy current brakes dynamometer system represented in the Simulink block is shown in Figure 3. The purpose of the analysis of the two types of PID and LQR controllers is to compare the system response.

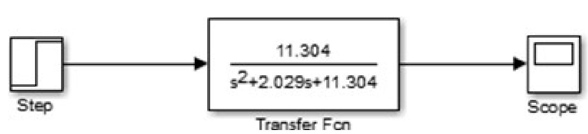

Figure 3. Simulink block of system eddy current breaks dynamometer open loop

2. PID control

Proportional, integral and derivative (PID) control is a type of control that is generally used in single input and single output (SISO) systems. The control system will compare the error signal with the input signal (set point) using proportional, integral and derivative parameters [10]. PID control is conventionally divided into two types, namely dependent on Eq (7) and independent in Equation (8). If expressed in terms of the transfer function in the s domain it becomes Equation (9)-(10). Where u is the controller output, e is the error value, Kp is the proportional constant, Ki is the integral constant and Kd is the derivative constant.

$$u(t) = K_p\left[e(t) + \frac{1}{\tau_i}\int e(t)dt + \tau_d \frac{d}{dt}e(t)\right] \quad (7)$$

$$u(t) = \left[K_p e(t) + K_i \int e(t)dt + K_d \frac{d}{dt}e(t)\right] \quad (8)$$

$$u(s) = K_p\left[1 + \frac{1}{\tau_i s} + \tau_d s\right]e(s) \quad (9)$$

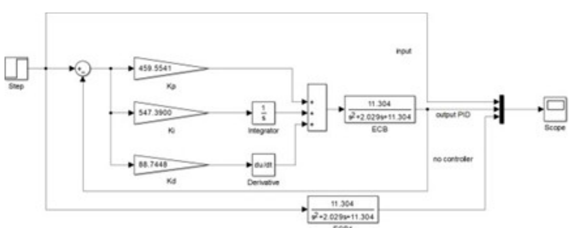

Figure 4. Simulink Block of system eddy current brakes dynamometer with PID

3. LQR control

Proportional control Linear Quadratic Regulator (LQR) control is a system optimization with state space representation. LQR has the same structure as pole placement, namely using full state feedback, but the difference between LQR and pole placement is how to determine the K matrix as the feedback gain [6]. The control block diagram of the LQR full state feedback system in the Eddy current brakes dynamometer system is presented in Figure 5.

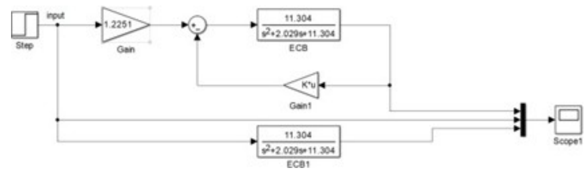

Figure 5. Simulink Block of system eddy current brakes dynamometer with LQR

Pole placement control has a weakness in finding the gain matrix K which is used to move the system pole to the desired pole. These weaknesses refer to aspects of system effort that are often not considered. This results in high energy consumption for actuator performance when trying to stabilize the system response. Through LQR control, this problem can be solved using the gain matrix K which is obtained from the Q and R matrices in the LQR control system concept. The LQR control system has the ability to optimize the gain matrix K by considering system performance and effort factors by optimizing the system performance index [2][8]. The optimal performance index is obtained by minimizing the performance index value in Equation (10).

$$J = \int^{\infty}\left(x^T Q x + u^T R u\right)dt \quad (10)$$

Through Equation (16) there is a symmetric real Q matrix which is positive definite (or positive semidefinite) and a symmetric real R matrix which is positive definite. The Q matrix is used to regulate the performance of the system so that it is related to the system state vector, while the Q matrix influences the steady state error value in the system response, the greater the Q value, the smaller the steady state error value. The R matrix is used to modify each input state in the system to achieve the desired gain, this will affect the efficiency of the actuator's performance to stabilize the system. The R matrix will play a role in controlling each input state in the system in order to regulate the level of effort efficiency of an actuator. Through the performance index equation, the gain K value can be calculated using the equation as shown in Equation (11). Matrix P is the solution of the Riccati equation which is represented in Equation (12).

$$K = R^{-1}B^{T}P \quad (11)$$

$$A^{T}P + PA - PBR^{-1}B^{T}P + Q = 0 \quad (12)$$

However, the conditions that must be met before designing a control design using LQR are that the system must be controllable. That means the input signal u can control the dynamics of each state vector variable x.

4. Zero steady state error

The results of designing full state feedback control using the LQR method produce a transient response that is in accordance with the desired criteria, however there are problems with the steady state error response. This problem is the difference between the input response and the system output in an infinite time. The input response in question is input from a closed loop system, or in other terms it is called a reference value or set point (Ferdinandus, 2018). Zero steady state error analysis is carried out after it is known that the system has reached stability. This analysis is used to correct system errors so that they reach zero steady state error conditions, which means there are no errors in steady state conditions. There are several methods of zero steady state error analysis, namely using a non-feedback input reference gain using Nbar N and/or using integral control (Ke). However, in the discussion regarding the design of LQR Eddy current brakes dynamometer control, this uses a steady state error with a reference input gain of Nbar (N) which will produce a system response of zero steady state error when given a step signal input. So the control system design structure can be described as in Figure 5, which is denoted by gain N. The gain value can be calculated with Equations (13) and (14), or with Equation (15) as the control signal equation. Then the gain N can be obtained in Equation (16).

$$\begin{bmatrix} N_x \\ N_u \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (13)$$

$$u = -Kx + (N_u + KN_x)r \quad (14)$$

$$u = -Kx - \bar{N}r \quad (15)$$

$$\bar{N} = N_u + KN_x \quad (16)$$

From all theoretical calculations starting from system modeling, PID control design design by determining the parameters Kp, Ki and Kd which are adapted from the Ackerman pole placement equation, then LQR control design by determining the Q matrix and R matrix to determine the full state feedback gain K and for achieving zero steady state error conditions using a gain reference input is done by computing in Matlab. The computational results are then simulated for each implementation of PID and LQR control on the Eddy current brakes system using Simulink.

Results and Discussions

After obtaining the characteristics in open loop conditions, PID and LQR control design is carried out. The control design was carried out based on the application of literature review theory as a basis for designing the control of the Eddy current brakes dynamometer system in Matlab /Simulink simulation. The following is the basic equation used for control design.

1. PID control result

The value of Ka gain full state feedback is use the "acker" command in Matlab. After getting it Ka value can then obtain the value of K^, through the value of K^ the values of Kp, Ki and Kd can be obtained. Through all this calculation assumes the best pole location is [-1 -5.2 -999] using Matlab calculations to obtain values of Kp = 459.5541, Ki = 547.3900 and Kd = 88.7448. After obtaining the PID parameter values, the system response was simulated using Simulink with a system model in the form of state space as in Figure 4 which produced an Eddy current brakes system response with 5 N braking force input using PID control as in Figure 5.

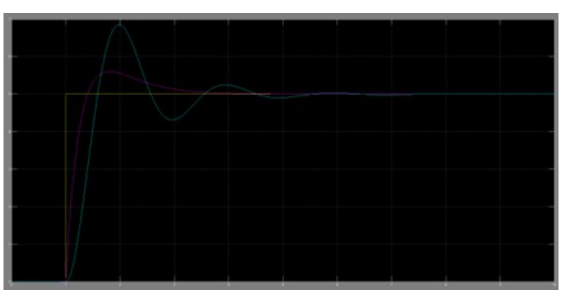

Figure 5. PID Waveform result

Based on the system response in Figure 7, the settling time (Ts) value is around 0.27 seconds, which is still classified as complying with the criteria, namely less than 5 seconds. However, this value is very unrealistic because the system response in real conditions is not possible in less than 1 second. Likewise for the rise time (Tr) value which is around 0.18 seconds. Apart from that, after being controlled using PID control, an overshoot value of 0.7% was still obtained. These results show that the use of a PID controller produces a system response that can achieve stability in accordance with the criteria, even though it experiences a significant increase in gain with a gain of around 5.7 N in less than 1 second.

2. LQR control result

Calculation of gain K via Equation (11) from solving Equation (12) with the Q and R matrix values in the first test as seen in Equation (17).

$$Q = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, R = 1 \quad (17)$$

From the first, it produces a gain gain value K = [0.8025 0.3181]. Addition of input reference gain obtained a strengthening value of 1.2251. After obtaining the reference input gain value to achieve zero steady state response, the response of the Eddy current brakes system with LQR control was tested using Matlab. Testing the response of Eddy current brakes using Simulink with a model in state space as in Figure 5 produces a braking time response as in Figure 6.

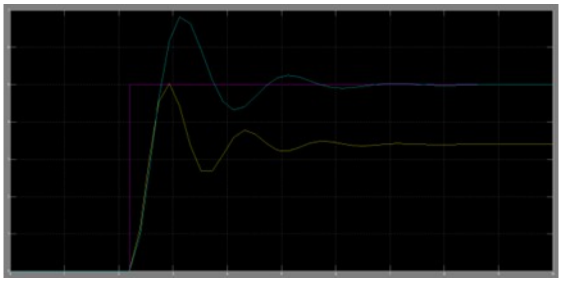

Figure 6. LQR Waveform result

2.19 seconds is good because it is still below the criteria limit of 5 seconds and is still in accordance with real conditions. From the first experiment, it was necessary to improve the values in the Q and R matrices to be able to increase the response to 5 N and improve the overshoot percentage value to 0 %. In the second test, the Q and R Matrix values were modified, which then obtains the gain value K = [2.7815 0.0117]. Next, the gain value is Nbar, $\bar{N}$ is obtained as 1.0083

Q = $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, R = 1

After modification, a response graph is obtained as shown in Figure 7. From this response, it can be seen that after improvements to the Q and R matrices and gain reference input $\bar{N}$ as pre-compensation, it can be seen that the system response can reach stability with a braking force value of 5 N without any overshoot. The settling time (Ts) value reached 2.12 seconds which met the criteria and the rise time (Tr) value was 1.18 seconds which also still met the predetermined criteria. The addition of N can increase the gain system output, so that it matches the value reference and achieve zero steady state error conditions. From the results of the second test using an LQR controller plus a gain reference input $\bar{N}$ is able to provide a braking response time that meets the criteria.

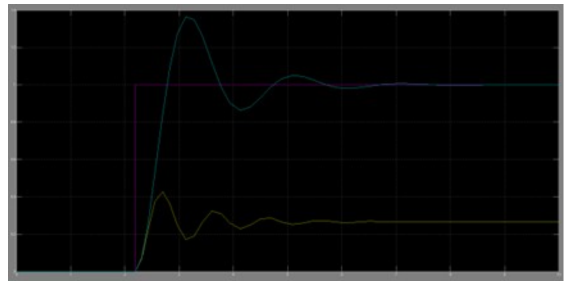

Figure 6. LQR Waveform type 2

3. Comparation Result

Table 2 shows that using LQR control can produce a better response time for Eddy current brakes compared to using PID control, this is because using LQR control produces transient response results that comply with the criteria with a settling time (Ts) value < 5 seconds and rise time (Tr) < 4 seconds which can still be said to be reasonable if implemented.

Table 2. Comparation

Criteria	PID	LQR
Settling time	0.27 s	2.12 s
Rise time	0.18 s	1.18 s
% *Overshoot*	0.7	0
Steady state error	0	0
Fb (breaks)	5 N	5 N

From the results of observing the system response, the use of LQR control can be said to be more optimal as a controller in the Eddy current brakes system because by using full state feedback LQR is able to regulate the performance for the dynamics of each system state vector using the Q matrix and regulate the efficiency of actuator performance via the system state vector input. using the R matrix, so that it can produce a more optimal system response with a transient response that meets the criteria.

Conclusion

The Eddy Current Brake system using PID control demonstrates a very fast transient response, with a settling time (sT) of 0.27 seconds, a rise time (rT) of 0.18 seconds, and an overshoot of 0.7%, which falls outside the desired system criteria. This response can be considered suboptimal for implementation in Eddy Current Brake systems because it requires a high level of effort to control the braking force response within such a short time. This results in excessive energy consumption to stabilize the braking force. Furthermore, when implemented in hardware, the excessively rapid braking response is inefficient and impractical.

A significant limitation of the PID control system lies in its reliance on parameters Kp, Ki, and Kd, which are inadequate for controlling the dynamics of every desired state variable within the Eddy Current Brake system. In contrast, the full-state feedback LQR control proves to be more precise and optimal for application in Eddy Current Brake systems. The LQR controller achieves a braking response that meets the desired criteria, with a settling time (sT) of 2.12 seconds, a rise time (rT) of 0.18 seconds, and no overshoot. This delayed braking response of 2 seconds reduces the controller's energy consumption, leading to more efficient control of the Eddy Current Brake system.

Thus, the modern LQR control method presents itself as a viable alternative to the classical PID control, which is still commonly used in Eddy Current Brake systems. By adopting the LQR method, braking force performance can be enhanced, achieving better energy efficiency and optimized control dynamics. This advancement aligns with the goals of community skill development, as it encourages the adoption of modern control techniques in practical applications, providing community members and professionals with opportunities to learn and apply innovative, energy-efficient technologies in automotive and industrial sectors.

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