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Doğrusal Olmayan Manyetik Levitasyon Sisteminin Kontrolü için PID ve LQR Kontrolcülerinin Performans Karşılaştırılması

Performance Comparison of PID and LQR Controllers for Control of Non-Linear Magnetic Levitation System

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Öz

Manyetik Levitasyon Sistemi (MLS), düşük enerji tüketimi ve minimum sürtünme gibi avantajlarından dolayı mühendislik alanında güncel bir çalışma haline gelmiştir. MLS'ler doğrusal olmayan kararsız sistemlerdir. Yapının karmaşıklığı ve kontrollerin zorluğu nedeniyle bu sistemler üzerinde birçok gelişmiş kontrol teorisi uygulanabilmekte ve kontrolörlerin performansı değerlendirilebilmektedir. Bu makalede, MATLAB ortamında matematiksel olarak modellenen MLS üzerinde, Oransal–İntegral–Türev (PID) ve Lineer-Quadratic Regulator (LQR) denetleyici yöntemleri uygulanmıştır. Bulunan sonuçlarda denetleyici performansları karşılaştırılmıştır. PID ve LQR kontrol yöntemlerinin MLS için uygulanabilirliği konusunda elde edilen sonuçlar değerlendirilmiştir. Ayrıca kontrolörlerin sistem performansı bakımından beş parametre ile karşılaştırılmıştır. Bunlar yükselme zamanı, yerleşme zamanı, maksimum aşma, aşma ve kararlı durum hatasıdır. LQR kontrolör, PID kontrolöre kıyasla büyük bir kararlılık ve homojen yanıt üretmiştir.

Anahtar Kelimeler: *Manyetik Levitasyon Sistemi, PID Kontrol, LQR Kontrol, Doğrusal Olmayan Sistem Kontrol*

Abstract

Magnetic Levitation System (MLS) has become a current study in the field of engineering due to its advantages such as low energy consumption and minimum friction. MLSs are nonlinear unstable systems. Due to the complexity of the structure and the difficulty of the controls, many advanced control theories can be applied on these systems and the performance of the controllers can be evaluated. In this article, Proportional-Integral-Derivative (PID) and Linear-Quadratic Regulator (LQR) controller methods are applied on MLS mathematically modeled in MATLAB environment. Controller performances were compared in the results found. The results obtained on the applicability of PID and LQR control methods for MLS were evaluated. In addition, the system performance of the controllers was compared with five parameters. These are rise time, settling time, maximum overshoot, overshoot and steady-state error. LQR controller produced great stability and homogeneous response compared to PID controller.

Keywords: *Magnetic Levitation System, PID Control, LQR Control, Non-linear System Control*

1. Introduction

Today, many systems consist of electromechanical equipment. When a mechanical system is combined with an electronic device, a new system is created that must be controlled by a controller. In this context, many methods can be used as a controller. However, some of these methods are difficult to design and increase the controller cost. Therefore, it is necessary to focus on lower cost control methods. MLS is one of the best examples of these electromechanical systems. A controller to be designed to control MLS should both produce fast results and be easy to design. Magnetic levitation technology is a system used to achieve better performance in many motion systems such as precision positioning and suspension due to their non-contact, multiple Degrees of Freedom (DOF) and long lifetime [1]–[4]. It is applied in many fields such as suspension systems, magnetic shaft bearing systems, anti-vibration and transportation systems. MLS is inherently non-linear and indecisive. Therefore, examining the control performance of MLS is of great importance. Various techniques have been applied to control MLS [5]. In [6], it is controlled using a real MLS PID. In a feedforward and multilayer neural network is used to model MLS, in which learning, and control are performed simultaneously. In addition, some studies based on neural networks have also been carried out [7]. Also, techniques of adaptive controllers for MLS are reviewed in [8], [9]. In [10], controllers created with artificial neural network techniques are designed for the control of nonlinear systems. In [11], optimal controllers based on iterative adaptive dynamic programming for MLS have been proposed and tested. A variety of methods have been designed and tested with the PI controller for the control of MLS [12]–[15]. A study was carried out on the optimum control of the MLS by calculating the PID parameters with the help of genetic algorithm [16].

A study has been carried out on setting the optimum PID controller parameters based on LQR for the control of MLS [17]. A study has been made on the real-time design and testing of different control techniques for an MLS with the SIMLAB platform [18]. Various systems have been controlled with intelligent control methods [19]–[23]. It can be controlled using MLS, PID and LQR methods [24], [25], [26]. Because there are many factors affecting the control of MLS, it attracts the attention of researchers working on control systems [27], [28], [29]. Many studies have been carried out to analyze the results by applying different control methods on the control of MLS [30], [31], [32]. Therefore, it appears as a current issue [33]. LQR and PID control methods are used together to control systems in many applications [34]–[38].

MLS is an issue to consider as it has indecisive and non-linear dynamics. It requires measurements of position, velocity and electric current values. Therefore, the space state equations must be analyzed to predict the non-existent signals of the nonlinear dynamical system. Considering the work mentioned, a controller that will stabilize this system is of great importance. In this study, a space state model and PID and LQR controllers are designed to control MLS based on Matlab/Simulink platform. Control systems were compared under the determined parameters. PID controller is used in the control of many systems [39].

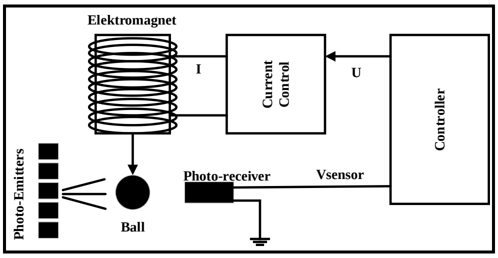
The main goal of this study is to examine the effects of LQR and PID control methods on a nonlinear system. In line with this goal, the controller performances created by MLS's PID and LQR controllers were examined. In the results found, it is seen that the LQR control method is more effective in controlling MLS than the PID control method. It is seen that the LQR controller designed in this context can be used effectively in non-linear systems.

When the studies in the literature are examined, it is clearly seen that MLS is frequently used in testing the designed controllers. When the studies in the literature are examined, it is clearly seen that PID and LQR control methods are frequently used in the control of nonlinear systems. In the literature, it is seen that the LQR and PID control methods of MLS are used extensively. For this reason, as a result of testing MLS with LQR and PID control methods and comparing the results found, it will shed light on researchers who want to work on this subject in the literature.

This study consists of six main parts. In the first chapter, the general purpose of the study, the cause-effect relationship and its place in the literature are explained. In the second part, the physical structure and properties of MLS are explained. In the third chapter, the dynamic properties and mathematical modeling of MLS are explained. In the fourth chapter, it is explained how the algorithms used in MLS control are created. In the fifth chapter, the comparison and interpretation of the designed LQR and PID controllers on MLS is explained. Finally, in the sixth chapter, the results and recommendations obtained from the study are explained.

2. Definition of MLS

The system that allows the steel ball to hang by controlling the tension of the coil forming the magnetic field creates the MLS discussed in this study and its schematic model is shown in Figure 1.



Şekil 1. MLS şematik model

Figure 1. MLS schematic model

Here I is the current used to control the electromagnet magnetic field strength. The position of the steel ball is detected by the optical sensor and transmitted to the controller as a Vsensor signal. The reference current value applied to the coil in the MLS is the output of the controller and is represented by U in Figure 1. The upward electromagnetic attraction force on the steel ball is controlled and adjusted to be equal to the weight of the ball. In this way, the steel ball is lifted into the air in balance. MLS is a highly indecisive and non-linear system in open loop control. For this reason, it is very important to design a controller with optimum performance.

3. MLS Dynamics and Modeling

Dynamic equations and modeling of MLS are explained in this section. Dynamic analyzes of MLS can be modeled by examining their electromagnetic and mechanical behavior. Here, this nonlinear MLS is mathematically modeled and then a linear model is presented.

3.1. Non-linear model of MLS

The nonlinear MLS model is expressed by the differential equations given below. The equations given below are based on electromagnetic modeling [40]. These equations can be expressed as follows using Newton's force and Kirchhoff's voltage laws.

$$V = \frac{dx}{dt} \tag{1}$$

$$m\ddot{x} = mg - C\left(\frac{i}{x}\right)^2 \tag{2}$$

$$u = iR + L\frac{di}{dt} - C\left(\frac{i}{x}\right)^2 \frac{dx}{dt} \tag{3}$$

The suspended steel ball has velocity V, position X, and mass m. L is the inductance of the coil. R is the resistance of the coil. I is the current of the coil. It is expressed by the magnetic force constant C. The gravitational acceleration is g. U is the voltage value applied to the system.

The time derivative of the position gives the velocity, and the time derivative of the velocity gives the acceleration. Based on this statement, which is known by everyone; We can define x=x1, v=x2 and i=x3.

Considering $x=x_1$, $v=x_2$ and $i=x_3$, Equations 1,2 and 3 can be written in matrix form as follows.

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \end{bmatrix} = \begin{bmatrix} x_2 \\ g - \frac{C}{m}\left(\frac{x_3}{x_1}\right) \\ -\frac{R}{L} + \frac{2C}{L}\left(\frac{x_3 x_2}{x_1^2}\right) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} \tag{4}$$

$$y = [x_1 \quad x_2 \quad x_3]^T = [1 \quad 0 \quad 0] \tag{5}$$

$$\dot{x} = f(x) + g(x)u \tag{6}$$

3.2. Linear model

The equations of state for a nonlinear system can be expressed as follows [41], [42].

$$\frac{dx(t)}{dt} = f[x(t), r(t)] \tag{7}$$

Here, x(t) is a (nx1) dimensional state vector, and r(t) is an (px1) dimensional input vector. f[x(r), r(t)] is a vector function of (nx1) dimensional state and input vectors in general.

The nominal operating trajectory against the nominal input $r_0(t)$ at a given initial state can be expressed as $x_0(t)$. If the nonlinear state equation shown in Equation 7 is expanded to a Taylor series around $x(t)=x_0(t)$ and all higher order terms are eliminated, equation 8 is obtained, with i=0, 1, 2, ..., n. is done.

$$\begin{aligned}\dot{x}_i(t) &= f_i(x_0, r_0) \\ &+ \sum_{j=1}^{n} \frac{\partial f_i(x,r)}{\partial x_j}|_{x_0,r_0}(x_j - x_{0j}) \\ &+ \sum_{j=1}^{p} \frac{\partial f_i(x,r)}{\partial r_j}|_{x_0,r_0}(r_j - r_{0j})\end{aligned} \tag{8}$$

Moreover,

$$\Delta x_i = x_i - x_{0i} \tag{9}$$

and

$$\Delta x_i = x_i - x_{0i} \tag{10}$$

if differences are identified,

$$\Delta \dot{x}_i = \dot{x}_i - \dot{x}_{0i} \tag{11}$$

relationship is provided.

Equation 8,

$$\dot{x}_{0i} = f_i(x_0, r_0) \tag{12}$$

because of,

$$\begin{aligned}\Delta \dot{x}_i &= + \sum_{j=1}^{n} \frac{\partial f_i(x,r)}{\partial x_j}|_{x_0,r_0}\Delta x_j \\ &+ \sum_{j=1}^{p} \frac{\partial f_i(x,r)}{\partial r_j}|_{x_0,r_0}\Delta r_j\end{aligned} \tag{13}$$

can be written as.

Equation 14 is obtained if equation 13 is written in vector-matrix form.

$$\Delta \dot{x} = A^* \Delta x + B^* \Delta r \tag{14}$$

Here,

$$A^* = \begin{bmatrix} \frac{\partial f_1}{x_1} & \cdots & \frac{\partial f_1}{x_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_n}{x_1} & \cdots & \frac{\partial f_n}{x_n} \end{bmatrix} \tag{15}$$

$$B^* = \begin{bmatrix} \frac{\partial f_1}{r_1} & \cdots & \frac{\partial f_1}{r_p} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_p}{r_1} & \cdots & \frac{\partial f_p}{r_p} \end{bmatrix} \tag{16}$$

is defined as.

When the system is linearized around the fixed equilibrium point $x=x_{01}$, the equation in which the velocity and acceleration terms will be zero at equilibrium can be determined as follows.

$$x_{02}(\mathrm{t}) = \frac{dx_{01}(t)}{dt} = 0 \tag{17}$$

$$\frac{d^2 x_{01}(t)}{dt^2} = 0 \tag{18}$$

For the nominal value of i(t) in equilibrium, if equation 18 is substituted in equation 3, equation 19 is obtained.

$$x_{03} = x_{01}\sqrt{\frac{gm}{C}} \tag{19}$$

For the designed system, the linearized state equations in equation 13 can be expressed as in equation 20.

$$\Delta \dot{x}(\mathrm{t}) = A^* \Delta x(t) + B^* \Delta \mathrm{u}(t) \tag{20}$$

In this case, the A^* and B^* matrices in the linearized state equations are obtained in the form in equation 21.

$$A = \begin{bmatrix} 0 & 1 & 0 \\ Cx_{03}^2 & 0 & -2\frac{Cx_{03}}{mx_{01}^2} \\ 0 & 2\frac{Cx_{03}}{Lx_{01}^2} & -\frac{R}{L} \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} \tag{21}$$

The C matrix for the output function can be expressed as in equation 22.

$$C = [1 \quad 0 \quad 0] \tag{22}$$

The equations given in Equations 21 and 22 represent the space state equations of MLS. LQR and PID controllers are designed on the basis of these equations.

4. Design of PID and LQR Controllers

This section covers LQR based controller and PID controller development for MLS as follows. The physical values of the system to be controlled are presented in Table 1 [40]. Here, the weight of the steel ball and the position of the ball are used differently from other applications in the literature to express the originality of the study and the accuracy of the designed controllers.

Tablo 1. MLS parametreleri.

Table 1. MLS parameters.

Parameters	Unit	Value
Mass of steel ball, m	Kg	0.5
Gravitational acceleration, g	m/s2	9.8
Inductance of the coil, L	H	0.01
Coil resistance, R	Ohm	1
Constant value, C		0.0001
Position of ball, X_{01}	m	0.024
Speed, X_{02}	m/s^2	
Current, X_{03}	A	0.84

When the parameters given in Table 1 are applied to the state space equations given in equations 21 and 22, the following results are obtained.

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 1633.33 & 0 & -0.5833 \\ 0 & 29.17 & -100 \end{bmatrix} \quad (23)$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 100 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \quad (24)$$

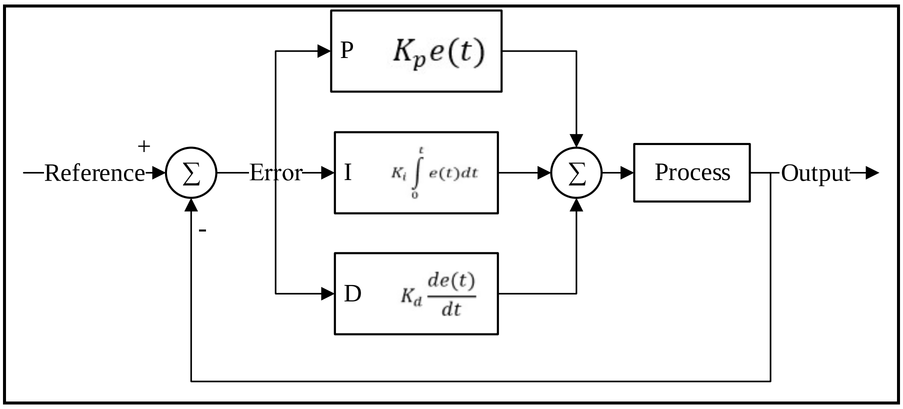
When the eigenvalue of the matrix A obtained in Equation 23 is calculated in Matlab environment, there are values of 40.3539, -40.5758, -99.7961. As a result of this process, it is determined that the system is indecisive in open loop control. The transfer function obtained from the equations in the linearized matrix form is given below.

$$T(s) = \frac{-55.33}{s^3 + 100s^2 + 1616s - 1.633e5} \quad (25)$$

The transfer function in the s domain of the PID control can be written as.

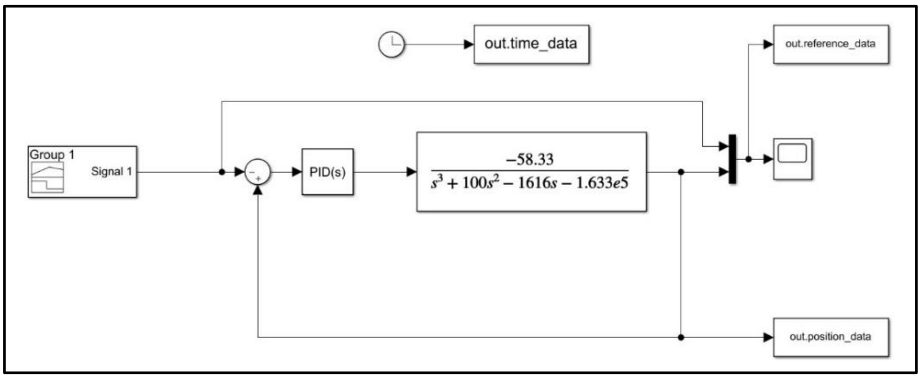
$$T_{PID}(s) = \frac{K_D s^2 + K_P s + K_i}{s} \quad (26)$$

Kp proportional gain expressed in Equation 26 is given as Ki integral gain and Kd derivative gain constant. The PID control method in MLS, modeled on Matlab/Simulink, successfully brought the system to reference value. Calculation of PID parameters was done with the help of Matlab/PID/Tuning toolbox. As a result of the calculations, it was found that P=23452, I=109803, D=623. Figure 2 shows the PID control structure. In Figure 3, Simulink model is given for controlling the system with PID. In Figure 3, Matlab/Simulink blocks of the MLS system modeled for PID control are given.



Şekil 2. PID kontrol yapısı

Figure 2. PID control structure



Şekil 3. MLS'nin PID kontrol modeli

Figure 3. PID control model of MLS

LQR control method is a control technique similar to the Root Locus approach by placing the closed loop poles of the system in the desired position [11]. The dynamic model used to linearize the MLS is formulated by the state space as follows:

$$\dot{x}(t) = Ax(t) + Bu(t) \tag{27}$$

$$y(t) = Cx(t) + Du(t) \tag{28}$$

The main purpose of the LQR control method is to minimize the performance index ($JLQR$). The performance equation of the LQR controller is given in Equation 29:

$$J_{LQR} = \frac{1}{2}\int_0^{\infty}(x^t(t)Qx(t) + u^T(t)Ru(t))dt \tag{29}$$

Here Q value and R value are considered as positive definite weight matrices. The P matrix given in equation 30 is provided by the Riccati equation for optimized control. The Riccati equation is given in Equation 31. The Q and R matrices selected for its control are given in Equation 32. The Q matrix was chosen based on the C state matrix. The R matrix was chosen according to the maximum acceptable error value and expert opinion. As a result, the K gain matrix of the LQR controller is calculated in Matlab by Equation 29. The controller is given in Equation 33. The LQR control structure is given in Figure 4.

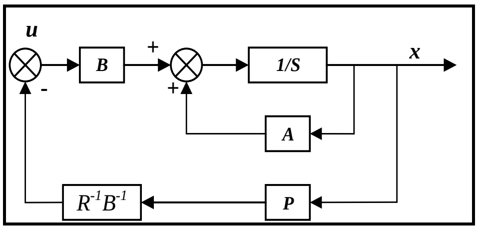
$$u^*(t) = -R^{-1}B^TPx(t) = -Kx(t) \tag{30}$$

$$A^TP + PA - PBR^{-1}B^TP + Q = 0 \tag{31}$$

$$Q = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, R = [10] \tag{32}$$

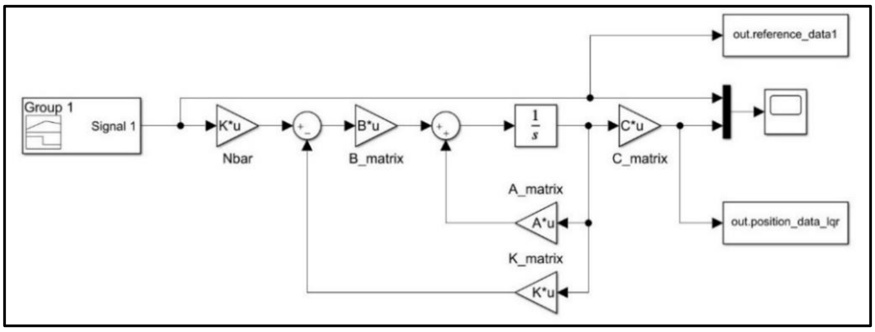
$$K = [-10180184860095500000 \quad -1221574119681380 \quad -251604991648962000] \tag{33}$$

After calculating the gain matrix of the LQR controller, it is used as input and feedback function in the MLS system modeled with the space-state model on Matlab/Simulink for the LQR control method. As a result of the experimental studies, it was seen that the model successfully brought the system to the reference value. In Figure 5, blocks of using MLS modeled on Matlab/Simulink for LQR control are given.



Şekil 4. LQR kontrol yapısı

Figure 4. LQR control structure



Şekil 5. LQR ile MLS'nin kontrol modeli

Figure 5. Control model of MLS with LQR

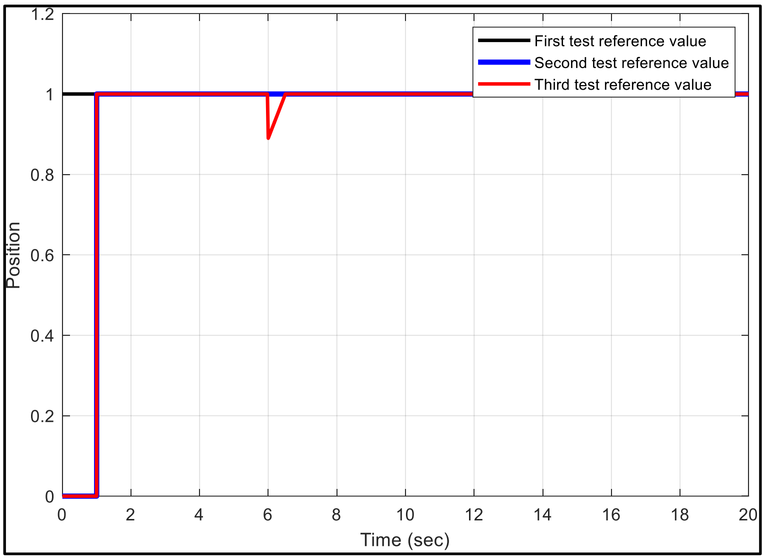
5. Experimental Studies

Simulation studies were carried out with Matlab/Simulink program to monitor and compare the performances of the designed PID and LQR control methods on MLS. As a reference value, the height value at which the steel bar should be hung was applied to the controllers. Both controllers must reach the reference value evenly. As a result of the experiments, the PID and LQR controllers successfully brought the MLS to the reference position point in a balanced way. The performances of the controllers designed with different experiments were examined. The control input signals used in the experiments are shown in Figure 6. A fixed reference value was applied as the first experiment and the responses produced by both controllers are shown in Figure 7. As a second experiment, the step function was applied and the responses produced by both controllers are shown in Figure 8. and in the final experiment, the step function was applied and the performances of the distortion counter controllers were compared and shown in Fig. A comparison of the results found for both controllers is shown in Table 2.

Tablo 2. PID ve LQR denetleyicilerinden alınan sonuçların karşılaştırılması.

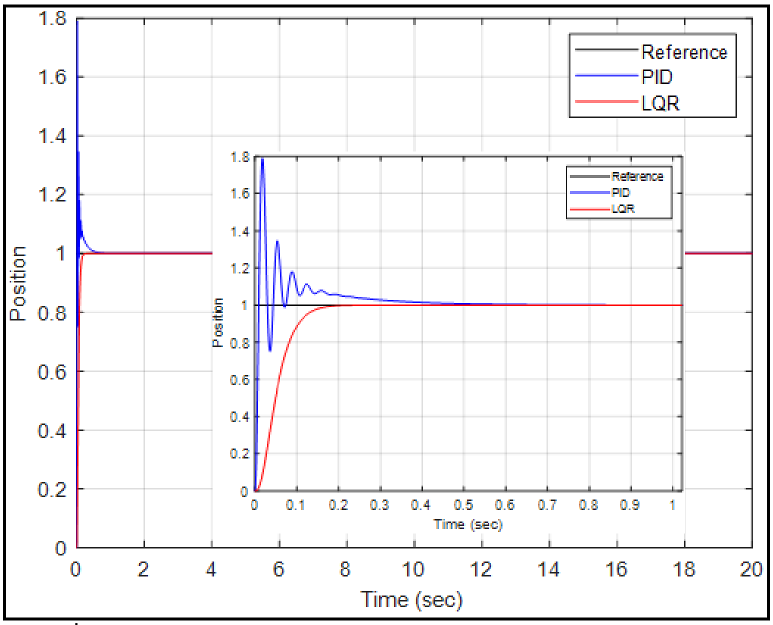
Table 2. Comparison of results from PID and LQR controllers.

Parameters	PID	LQR
Reference value	1	1
Rise time (sec)	0. 0059	0.0852
Setting time (sec)	0.3491	0.1524
Maximum overshoot (%)	79.031	0
Overshoot (mm)	1.7903	1
Steady state error (rad)	-1.3601e-08	3.7748e-15



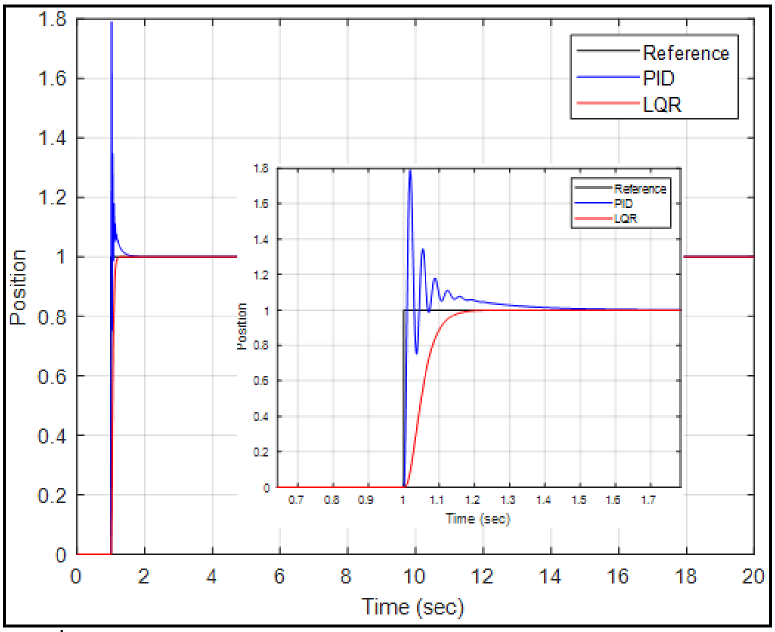
Şekil 6. Birinci, ikinci ve üçüncü deney için referans değerler

Figure 6. Reference values for the first, second and third experiment



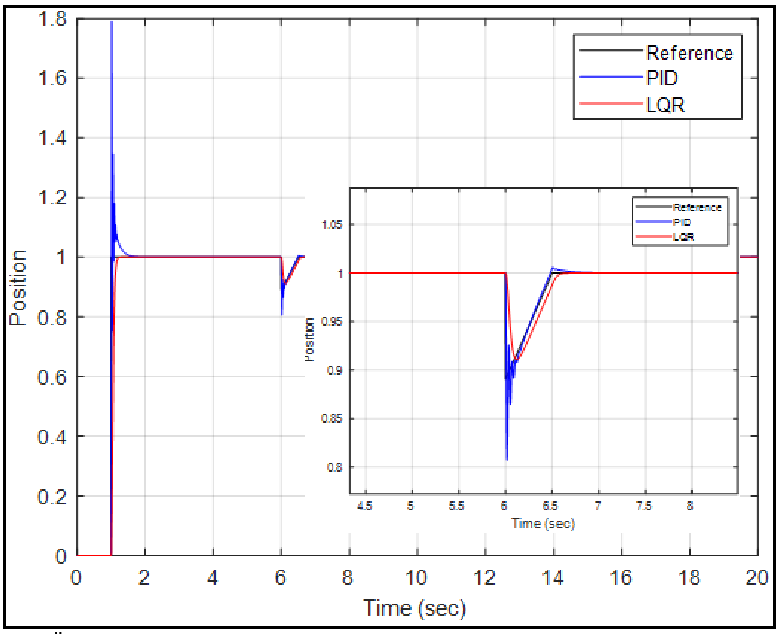
Şekil 7. İlk deney için PID ve LQR denetleyici performansının karşılaştırılması

Figure 7. Comparison of PID and LQR controller performance for the first experiment



Şekil 8. İkinci deney için PID ve LQR denetleyici performansının karşılaştırılması

Figure 8. Comparison of PID and LQR controller performance for the second experiment



Şekil 9. Üçüncü deney için PID ve LQR denetleyici performansının karşılaştırılması

Figure 9. Comparison of PID and LQR controller performance for the third experiment

6. Discussion and Conclusions

Today, smart control methods are used to control many systems. Especially in today's world, where the developing technology and human factor are tried to be minimized in the system, it is aimed to develop the existing control methods due to the complexity of the systems and to achieve more successful results in this way. Magnetic levitation systems are of great interest in the development of many control methods due to their non-linear nature and the difficulty of their control. In this study, PID and LQR control methods were applied on an unstable and non-linear system, the results were examined, and the methods were compared. Comparison of methods was made on an MLS model. According to the results obtained from the studies, both methods brought the steel ball, which was in the zero position at the beginning, to the target point in a balanced way. In studies performed with the PID method, the system reaches the desired value by exceeding the reference point. In studies conducted with the LQR control method, it is seen that it does not exceed the reference point and reaches the desired value in a much shorter time compared to the PID control method. In addition, it is seen that the LQR control method is more stable than the PID control method, as the response speed of the system and the dynamical disturbance effects will be faster to reach the reference value in the LQR method. In the simulations performed with the LQR method, the system is simulated to reach the target location at t=0.1524 s, and in the PID method at t=0.3491 s. As a result, it is recommended to use the LQR method as it gives a faster response to reach the reference value in MLS. As can be understood from the results found in general, it is clearly seen that the use of LQR control method in the control of nonlinear systems will both reduce the cost and improve the control performance. As a suggestion for future studies, LQR controller can be applied over different nonlinear systems. In addition, a faster and more efficient controller can be created by designing a hybrid controller.

6. Tartışma ve Sonuçlar

Günümüzde birçok sistemi kontrol etmek için akıllı kontrol yöntemleri kullanılmaktadır. Özellikle gelişen teknoloji ve insan faktörünün sistemlerde en aza indirilmeye çalışıldığı günümüzde, sistemlerin karmaşıklığından dolayı mevcut kontrol yöntemlerinin geliştirilmesi ve bu şekilde daha başarılı sonuçlara ulaşılması amaçlanmaktadır. Manyetik kaldırma sistemleri, doğrusal olmayan yapıları ve kontrollerinin zorluğu nedeniyle birçok kontrol yönteminin geliştirilmesinde büyük ilgi görmektedir. Bu çalışmada kararsız ve doğrusal olmayan bir sistem üzerinde PID ve LQR kontrol yöntemleri uygulanmış, sonuçlar incelenmiş ve yöntemler karşılaştırılmıştır. Yöntemlerin karşılaştırılması bir MLS modeli üzerinde yapılmıştır. Çalışmalardan elde edilen sonuçlara göre her iki yöntem de başlangıçta sıfır konumunda olan çelik bilyeyi dengeli bir şekilde hedef noktasına getirmiştir. PID yöntemi ile yapılan deneylerde sistem referans noktasını aşarak istenilen değere ulaşır. LQR kontrol yöntemi ile yapılan çalışmalarda PID kontrol yöntemine göre referans noktasını aşmadığı ve istenilen değere çok daha kısa sürede ulaştığı görülmektedir. Ayrıca LQR yönteminde sistemin tepki hızı ve dinamik bozucu etkiler referans değerine daha hızlı ulaşacağı için LQR kontrol yönteminin PID kontrol yöntemine göre daha kararlı olduğu görülmektedir. LQR yöntemi ile yapılan simülasyonlarda sistemin hedef konuma t=0,1524 s'de, PID yönteminde t=0,3491 s'de ulaştığı bulunan sonuçlarda görülmektedir. Sonuç olarak MLS'de referans değere ulaşmak için daha hızlı yanıt verdiğinden dolayı LQR kontrol yönteminin kullanılması tavsiye edilmektedir. Genel olarak bulunan sonuçlardan da anlaşılacağı üzere LQR kontrol yönteminin lineer olmayan sistemlerin kontrolünde kullanılmasının hem maliyeti düşüreceği hem de kontrol performansını iyileştireceği açıkça görülmektedir. Gelecekteki çalışmalar için bir öneri olarak, LQR denetleyici farklı doğrusal olmayan sistemler üzerinde uygulanabilir. Ayrıca hibrit bir kontrolör tasarlanarak daha hızlı ve verimli bir kontrolör oluşturulabilir.

7. Ethics committee approval and conflict of interest statement

“Ethics committee approval is not required for the prepared article.”

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