International
Journal
of Advanced Research in Engineering& Management (IJAREM)
ISSN: 2456-2033 || PP. 56-62

Controller Optimization of Magnetic Levitation System

Mehmet Şimşir*
** Mechatronics Engineering Department, Technology Faculty, Karabük University, Karabük, Turkey*

Abstract: Magnetic levitation systems are one of the popular structures in control applications. These systems are non-linear and it is possible to observe the performance of various types of controllers on these systems. Nowadays there are application areas like maglev train technologies, vibration isolation systems etc. While designing a controller, determination of the controller coefficients is complex, and the classical methods require long time for tuning process. With the help of optimization algorithms, the parameter tuning process of the controllers can be done in short time and it is possible to take an optimum performance from the controller. In this study, a magnetic levitation system is modeled and linearized. PID controller is designed for position control of the linearized model. The PID controllers are widely used in the industry and have enough performance for many applications. Increasing the performance of a PID controller is possible with optimization techniques. The coefficients of the designed controller are tuned using the Genetic Algorithm and the optimum values are found. As a result, the system's performance is developed sufficiently with short settling time and small overshoot.

Keywords: Magnetic levitation system, Genetic Algorithm, PID controllers, position control, optimization

I. INTRODUCTION

Engineering systems generally have some basic physical structures. Some of the popular systems are examined for studies about system mechanisms or controller design, like inverted pendulum and magnetic levitation systems [1], [2]. Magnetic levitation is one of the important phenomena of the physical control templates because it rewards in the industrial domain. Magnetic levitation has successfully been implemented and studied in various applications, such as maglev train technologies, vibration isolation systems etc. [1], [3]–[5] . There are also many studies about magnetic levitation with varied aspects. Qin et al. studied on a modeling and control approach for magnetic levitation system based on state-dependent Auto-regressive with exogenous input model. They built the model and represented the dynamic behavior between the current of electromagnetic coil and the position of the ball [6]. Bobstov et al. presented a parameter estimation based state observer model for sensorless control of magnetic levitation systems [7]. Ahmad and Javaid designed a non-linear dynamic model for magnetic levitation system and presented linear and nonlinear state space controllers[8].

There are also many studies about control strategies which are based on popular physical templates. Chopade at al. presented fractional order proportional integral derivative (PID) and integer order PID controller to control the position of the levitated object in a magnetic levitation system. [9]. Lin et al. proposed an intelligent backstepping control system using a recurrent neural network to control the moving position of a magnetic levitation apparatus to compensate for uncertainties, including friction force [10]. Fares et al. investigated the design of a controller for keeping a levitated steel ball using proportional derivative fuzzy controller [11]. Rubio et al. modeled and controlled the angular position of a levitated ball and approximated the magnetic parameters using neural networks [12]. Al-Muthairi and Zribi applied sliding mode controller to a magnetic levitation system [13]. Charara et al. presented a model of an inertial wheel, supported by active magnetic bearings. A non-linear controller based input-output linearization was derived to stabilize the model [14]. Humaidi et al. designed and analyzed an active disturbance rejection control (ADRC) method for controlling and disturbance rejection of a magnetic levitation system. They also compared the performances of linear and non-linear ADRC in terms of robustness against variation of parameters and the capability to reject applied disturbance [15]. Linear Quadratic Control is also a popular tool for linear control applications and parameter adjustment can be made using optimization algorithms [16].

Controller parameters are important components of the factors which affects the performance of controllers. It may not be possible to adjust these parameters with higher efficiency and performance using classical methods. Therefore, various optimization algorithms are used for optimizing the controller parameters.

Strumberger et al. presented a study about optimization of radial active magnetic bearings using differential evolution algorithm [17]. Wai et al. focused on the design of a real-time particle-swarm-optimization based PID controller for a maglev transportation system [18]. Erkol designed an optimal fractional order PID controller for a two-wheeled inverted pendulum and optimized the controller by Artificial Bee Colony, Grey Wolf Optimizer and Cuckoos Search algorithms [19]. He reported Artificial Bee Colony Algorithm had better performance among the compared algorithms. Erkol also used the Artificial Bee Colony Algorithm to optimize the controller of an inverted pendulum [20]. Genetic Algorithm is also a popular optimization technique which is used for solving many engineering problems. Masum et al. solved the vehicle routing problem using Genetic Algorithms [21], [22].

In this study, a magnetic levitation system, which is accepted as a popular system for controller design studies, was modeled mathematically. Proposed model was simulated by the help of MATLAB®. Then a position controller was designed for levitating a metal ball to a desired position. Controller parameters were optimized using Genetic Algorithm for a better performance of the controller.

II. MAGNETIC LEVITATION SYSTEM

The general structure of a magnetic levitation system is given in the Fig. 1. The system consists of a metal ball and an electro-magnet. A sensor is also required to measure the ball position. With the magnetic force applied to the electro-magnet, a gripping force is created that can hold the ball in the target position. The required amount of voltage is set by a controller. Z is the impedance of the electromagnet, fm is the magnetic force, fg is the gravitational force, fa is the the force originating from the acceleration and x is the ball position.

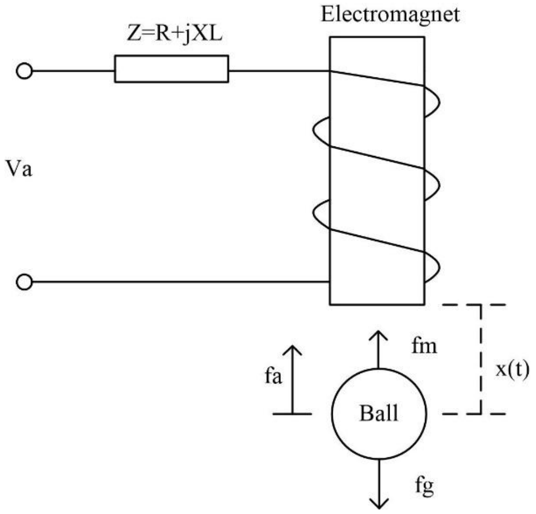

Figure 1. Block diagram of a magnetic levitation system

The mathematical equations of the system are given in (1)-(5). These are non-linear equations that define the system. For more information, see [23].

$$fm = K\left(\frac{i}{x}\right)^2 \quad (1)$$

$$fa = m\frac{d^2x}{dt^2} \quad (2)$$

$$fg = mg \quad (3)$$

$$\frac{d^2x}{dt^2} = g - \frac{K}{m}\left(\frac{i}{x}\right)^2 \quad (4)$$

$$\frac{di}{dt} = \frac{R}{L}i + \frac{1}{L}V \quad (5)$$

At the equilibrium point of the system, the derivative of position and the derivative of the current are equal to zero. In other words, the magnetic force and the gravitational force are equal to each other. They are given in (6)-(7). Using (4), the amount of current to be applied to the electromagnet at the equilibrium point can be obtained. The equation is given in (8). This equation is used to calculate the current value required for the equilibrium point for linearization.

$$\frac{d^2x}{dt^2} = 0 \quad (6)$$

$$\frac{di}{dt} = 0 \quad (7)$$

$$ie = xe\sqrt{\frac{mg}{K}} \quad (8)$$

The non-linear equations should be linearized for linear control with PID. The electrical equation is also linear. If the mechanical equation is linearized around xe, the space state equations given in (9) - (10) are obtained. x1, x2 and x3 represent the position, speed and current respectively. v(t) is the input voltage.

$$\begin{bmatrix} \dot{x1} \\ \dot{x2} \\ \dot{x3} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ \frac{2K(ie)^2}{mx^3} & 0 & \frac{-2K(ie)}{m(xe)^2} \\ 0 & 0 & -\frac{R}{L} \end{bmatrix} \begin{bmatrix} x1 \\ x2 \\ x3 \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \frac{1}{L} \end{bmatrix} v(t) \quad (9)$$

$$B = [0 \quad 0 \quad 1/L]' \quad (10)$$

III. GENETIC ALGORITHM

Genetic Algorithm (GA) is an evolution-based optimization algorithm. The basic structure of GA is built on transferring the individual characteristics to new individuals by chromosomes. It was firstly proposed by J. Holland [24], [25]. Evolution starts from random individuals and the best ones are selected, then their characteristics are transferred to new individuals. The number of the individuals in the population is fixed. Once the new individuals have occurred, weak ones are selected and removed from the population. The new population is used for the next iteration of the algorithm. By this way, the individuals in the population have always better characteristics.

In the Genetic Algorithm, each individual is represented by binary numbers. They are the chromosomes which have characteristics of the individuals. Operators such as crossing over, mutation and natural selection are used during the production of the new individuals. Crossing over is the process of producing a new chromosome by taking one piece from each of two different chromosomes. This is simply the process of combining random parts of binary numbers representing both chromosomes and generating a new number

Mutations are random changes in the chromosomes. In each iteration, a certain number of chromosomes are mutated by a probability-based parameter. Mutation is the process of changing some bits of a number. Thus, a new number which means a new chromosome is produced.

Population growth with new individuals is obtained by mutation and crossover. However, population size should be fixed. For this, natural selection process is applied. Natural selection means the survival of individuals which are stronger, and the weaker ones disappear. In the Genetic Algorithm, weak and strong individuals are determined by fitness function. According to the fitness function, the strong ones survive while the weak ones are destroyed.

The fitness function is a problem-specific function for the optimization process. It takes the problem parameters as inputs and produces a value proportional to the suitability of these parameters. This value is used in natural selection process. If the optimization problem is considered as a minimization problem, the chromosomes which have smaller objective function value will survive.

These processes are repeated in each iteration of the algorithm. The algorithm can be stopped by a certain number of iteration or criteria based on the fitness value. Detailed information can be seen in [24].

IV. PID CONTROLLER AND FITNESS FUNCTION

The PID controller is one of the most widely used controllers in the industry and has a sufficient performance for many applications. It consists of a combination of proportional control, integral control and derivative control. Classically, the parameters of PID controllers are adjusted by the Ziegler-Nichols method or by trial and error method. However, it is possible to obtain better performances using optimization algorithms for parameter tuning process. The structure of a PID controller in S-domain in parallel form is given in (11). Kp is the proportional gain, Ki is the integral gain and Kd is the derivative gain.

$PID(s) = Kp + sKd + \frac{Ki}{s}$ (11)

For the PID controller, a number of fitness functions have been proposed in the literature. Some of these are integral of absolute errors, integral of squared errors and integral of weighted absolute errors. The structure of the absolute errors used in this study is given in (12) [16], [19].

$IAE = \int_0^t |e(t)|dt$ (12)

V. EXPERIMENTAL STUDY

The magnetic levitation system modeled in this study was simulated by the MATLAB® program. A PID controller was used for position controlling and the control coefficients were adjusted by Genetic Algorithm. The general structure of the simulated system is given in Fig. 2. The error was generated by comparing the reference position with data received from the position sensor. The error was given as input to the PID controller and the controller output was the reference voltage required to drive the electromagnet. This reference voltage was generated by an adjustable power supply and the position of the ball was changed.

The system parameters were determined as follows: R=3.5Ω, g=9.81 m/s^2, L=0.01 H, K=$68.823.10^{-6}$ and m=$8.4x10^{-4}$ kg. The magnetic levitation system given in Part II is linearized at xe = 0.01m. The current at this point can be calculated by (13).

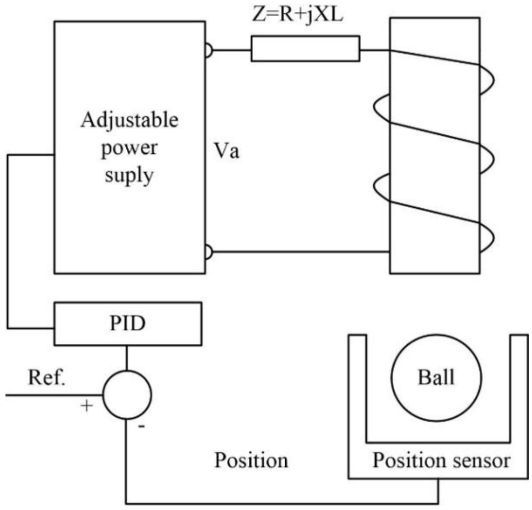

Figure 2. Block diagram of the simulated system

$ie = xe\sqrt{\frac{mg}{K}} = 0.3446A$ (13)

A, B, C and D matrices of linear state space equations, which were obtained by using equilibrium current, position and system parameters are given in (14) – (17).

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 1962 & 0 & -57.70 \\ 0 & 0 & -350 \end{bmatrix} \quad (14)$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 100 \end{bmatrix} \quad (15)$$

$$C = [1 \quad 0 \quad 0] \quad (16)$$

$$D = [0] \quad (17)$$

The obtained state space matrices were simulated using the MATLAB® program. A PID controller was added to the model. The input of the PID controller is the position error and the output is the required voltage applied to the magnetic levitation system. The system was optimized with the Genetic Algorithm using the optimization toolbox of the MATLAB® program. For this purpose, an improved fitness function was designed. The function given in (12) was used with the settling time value and overshoot value of the system output by providing a multi-objective fitness function and it is given in (18) [16], [19]. The ST denotes the settling time;

the OS is the overshoot value. The coefficient *"p"* of OS was set as 100 and determined by trial and error method. It has a high value to obtain a system with less overshoot.

$$IAE_i = \int_0^t |e(t)|dt + p.OS + ST \quad (18)$$

The position - time graph of the optimized system is shown in Fig. 3. As it can be seen, the position of the controlled ball was set at as 0.95s and had a low overshoot ratio as 28.25%. The total error of the system output was only 234.699. No aggressive behavior such as excessive oscillation was observed at the system output.

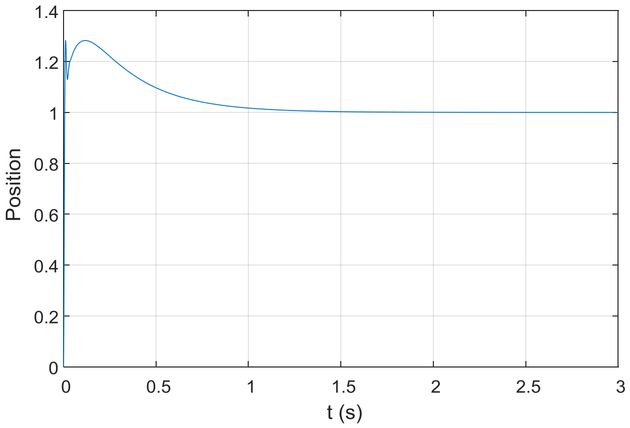

Figure 3. Position graph of magnetic levitation system

The fitness value versus generations graph of the Genetic Algorithm used in the optimization of the controller of magnetic levitation system is given in Fig. 4. The algorithm was run for 150 iterations. The PID controller's coefficients were limited in the range of +/- 1000 and the simulation was run for 1.5s during the optimization process. Population size was chosen as 50. Algorithm was reached the optimum value in the 127th iteration. A total error of 3061 was obtained with the most optimal control. The reason which makes this value greater than the value of the unit step response, is longer simulation time used during optimization process.

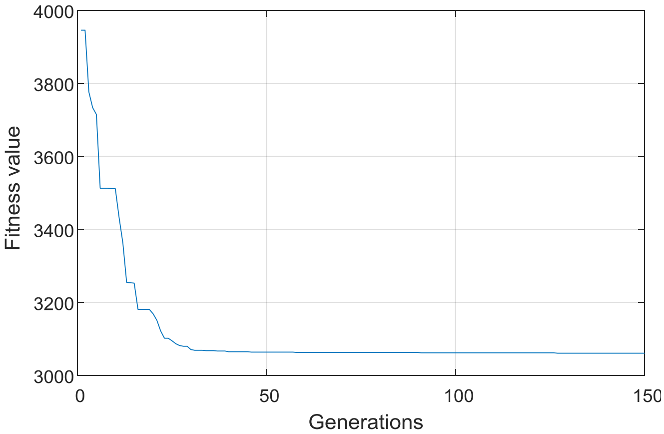

Figure 4. Fitness value – generations graph of optimization process by Genetic Algorithm

VI. CONCLUSION

In this study, a magnetic levitation system was modeled, and linear equations were obtained. The equilibrium point of the system was 0.01 m. The system is controlled by a PID controller. Adjustment of PID controller coefficients was realized by using Genetic Algorithm Toolbox of MATLAB®.

The obtained system had a settling time of 0.95s and a maximum overshoot of 28.25%. These values are suitable for using in the physical applications. The total error of the system output is only 234.699. There is no excessive vibration and no big overshoot at the system output.

The results show that the Genetic Algorithm is successful in parameter setting of the PID controller used in position controlling of the magnetic levitation system. In addition, various optimization techniques can be examined to obtain better results. The implementation of this study in a physical system and its comparison with various optimization algorithms are among the plans of the future studies.

REFERENCES

[1] A. El Hajjaji and M. Ouladsine, Modeling and nonlinear control of magnetic levitation systems, *IEEE Trans. Ind. Electron.*,48(4), 2001, 831–838.

[2] J. Li, Z. Deng, C. Xia, Y. Gou, C. Wang, and J. Zheng, Subharmonic Resonance in magnetic levitation of the high-temperature superconducting bulks YBa2Cu3O7-x under harmonic excitation, *IEEE Trans. Appl. Supercond*., 29(4), 2019, 1–8.

[3] L. Hyung-Woo, K. Ki-Chan, and L. Ju, Review of maglev train technologies, *IEEE Trans. Magn.*,42(7),2006, 1917–1925.

[4] K. Nagaya and M. Ishikawa, A noncontact permanent magnet levitation table with electromagnetic control and its vibration isolation method using direct disturbance cancellation combining optimal regulators," *IEEE Trans. Magn.*,31(1), 1995, 885–896.

[5] T. Mizuno, M. Takasaki, D. Kishita, and K. Hirakawa, Vibration isolation system combining zero-power magnetic suspension with springs, *Control Eng. Pract*., 15(2), 2007, 187–196.

[6] Y. Qin, H. Peng, W. Ruan, J. Wu, and J. Gao, A modeling and control approach to magnetic levitation system based on state-dependent ARX model, *J. Process Control*,24(1), 2014, 93–112.

[7] A. A. Bobtsov, A. A. Pyrkin, R. S. Ortega, and A. A. Vedyakov, A state observer for sensorless control of magnetic levitation systems, *Automatica,* 97, 2018, 263–270.

[8] I. Ahmad and M. A. Javaid, Nonlinear model & controller design for magnetic levitation system, *ISPRA Proc. 9th WSEAS Int. Conf. Signal Process. Robot. Autom*.,2010, 324–328.

[9] A. S. Chopade, S. W. Khubalkar, A. S. Junghare, M. V. Aware, and S. Das, Design and implementation of digital fractional order PID controller using optimal pole-zero approximation method for magnetic levitation system, *IEEE/CAA J. Autom. Sin.*, 5(5), 2018, 977–989.

[10] F. J. Lin, L. T. Teng, and P. H. Shieh, Intelligent adaptive backstepping control system for magnetic levitation apparatus, *IEEE Trans. Magn*., 43(5), 2007, 2009–2018.

[11] A. H. Fares, A. Abdelfattah, A. B. Sharkawy, and A. A. Abo-Ismail, Intelligent control of magnetic levitation system, *J. Eng. Sci. Assiut Univ.*,37(4),2009, 909–924.

[12] J. de Jesús Rubio, L. Zhang, E. Lughofer, P. Cruz, A. Alsaedi, and T. Hayat, Modeling and control with neural networks for a magnetic levitation system, *Neurocomputing*, 2278(September), 2017, 113–121.

[13] N. F. Al-Muthairi and M. Zribi, Sliding mode control of a magnetic levitation system, *Math. Probl. Eng*., 2004(2), 2004, 93–107.

[14] A. Charara, J. De Miras, and B. Caron, Nonlinear control of a magnetic levitation system without premagnetization" *IEEE Trans. Control Syst. Technol*., 4(5), 1996, 513–523.

[15] A. J. Humaidi, H. M. Badr, and A. H. Hameed, PSO-Based active disturbance rejection control for position control of magnetic levitation system, *5th Int. Conf. Control. Decis. Inf. Technol*., 2018, 922–928.

[16] H. O. Erkol, Linear quadratic regulator design for position control of an inverted pendulum by grey wolf optimizer, *Int. J. Adv. Comput. Sci. Appl.*, 9(4), 2018, pp. 13–16.

[17] G. Stumberger, D. Dolinar, U. Pahner, and K. Hameyer, Optimization of radial active magnetic bearings using the finite element technique and the differential evolution algorithm, *IEEE Trans. Magn.*, 36(4), 2000, 1009–1013.

[18] R. J. Wai, J. D. Lee, and K. L. Chuang, Real-time PID control strategy for maglev transportation system via particle swarm optimization,*IEEE Trans. Ind. Electron*., 58(2), 2011, 629–646.

[19] H. O. Erkol, Optimal (PID mu)-D-lambda controller design for two wheeled inverted pendulum,*IEEE Access*, 6, 2018, 75709–75717.

[20] H. O. Erkol, "Optimization of an inverted pendulum system by the artificial bee colony algorithm,*J. Polytech*., 20(4), 2017,863–868.

[21] A. K. M. Masum, M. F. Faruque, M. Shahjalal, M. Iqbal, and H. Sarker, Solving the vehicle routing problem using Genetic Algorithm, *Int. J. Adv. Comput. Sci. Appl*., 2(7) 2011, 126–131.

[22] N. Tutkun, Improved power quality in a single-phase PWM inverter voltage with bipolar notches through the hybrid Genetic Algorithms, *Expert Syst. Appl.*, 37(8), 2010, 5614–5620.

[23] M. I. Sorour, *Designing Two-Dimensional Magnetic Levitation Control System*, The Islamic University, *Gaza*, 2015.

[24] D. E. Goldberg and J. H. Holland, Genetic algorithms and machine learning, *Mach. Learn*., 3, 1988, 95–99.