Proceedings of the International Conference on Electronics and Sustainable Communication Systems (ICESC 2020)
IEEE Xplore Part Number: CFP20V66-ART; ISBN: 978-1-7281-4108-4

Trajectory Tracking and Ball Position Control of Magnetic Levitation System using Swarm Intelligence Technique

Ankita Varshney
Electrical Engineering Department
Delhi Technological University,Delhi, India
ankitavarshney_mt2k18@dtu.ac.in

Bharat Bhushan
Electrical Engineering Department
Delhi Technological University, Delhi, India
bharat@dce.ac.in

Abstract— **Magnetic levitation system is a second-order non-linear system. The objective of the system is to levitate a metallic ball at a determined height under the influence of magnetic force by the principle of non-contact. In this paper, particle swarm optimization (PSO) technique is used to develop a controller to regulate the nonlinear dynamics in the magnetic levitation system. The proposed technique acts in parallel with a proportional integral derivative (PID) controller to balance the position of levitating ball in the air. Here, the optimization technique tunes the gain values of the PID controller for achieving better performance measures when applied to a nonlinear system. This tuning process adheres to search the optimal solution with the help of agents called as particles whose trajectories are adjusted by a deterministic component. Each particle is optimized by its best-achieved position through the iterative approach. Further, the performance of the proposed controller is demonstrated through simulation as well as on hardware. Both PID and PSO tuned PID controllers were designed and the dynamics of magnetic levitation system were tested. The results validate the performance of both conventional PID controller as well as PSO tuned PID controller enhancing the operation of the magnetic levitation system. It is observed that the PSO tuned PID overcomes the drawback of conventional PID by optimizing the performance parameters such as steady-state error and settling time.**

Keywords- Particle swarm optimization (PSO), Zeigler Nicholas (Z-N) method, PID controller, Linear quadratic regulator (LQR), Magnetic levitation system (MLS)

I. INTRODUCTION

Magnetic levitation system also is known as Maglev is characterized as a method where an object achieves equilibrium in air space under the influence of magnetic fields only. The gravitational pull acting on the ball is balanced by the magnetic force generated through the electromagnetic coil. The force produced should be sufficient enough to not only counteract gravity but other accelerations also such as disturbance due to external noise and environmental effects acting on the system. Now a day's magnetic levitation system is having many applications such as in magnetic levitation vehicles, maglev wind turbines, maglev micro-robots, and magnetic levitation bearings [1]-[3]. Magnetic levitation systems can be categorized as attractive and repulsive systems based on the orientation of the source of levitating forces. These types of systems are unstable and highly nonlinear in nature. High-performance feedback controllers are required to control the ball position movement in Maglev systems [1]. The two primary issues involved in the levitation process are the lifting forces that are used to counteract the gravitational pull and the other is to ensure the stability of the ball, that it must not flip into the same orientation where the lift on the ball is neutralized. To balance the ball in the air without oscillations and to follow the desired path trajectory, the designing of an excellent tracking controller is required. The disturbances and noise present in the environment make the ball to move in the unbalanced region, so the control action produced should be strong enough to deal with external disturbances and keep the ball in equilibrium [2].

From the literature, it has been observed that many control techniques have been developed for ball position control of a magnetic levitation system. In classical control design, the PID controller has been implemented for tracking and controlling of the levitated ball position of magnetic levitation system. PID controllers are classical controllers and are designed as a combination of (P), (I) and (D) controller. The PI control action is performed in the low-frequency region, whereas PD control action takes place in the high-frequency region [3]. Using a PID controller the improvement can be observed on both steady and transient state of the system. Parameters of the PID controller are calculated using classical tuning methods such as Ziegler-Nichols (Z-N) method, Cohen-coon method and hit and trial also. The Z-N rules provide PID parameter values and give a starting point for fine-tuning, rather than providing final setting values for PID controller gain parameters. A robust PID controller was designed for an unstable Maglev system based on frequency domain analysis to ensure the stability of the system in terms of gain margin and phase margin [4]. PID controllers are easy to implement but have a drawback that they require a complete linearized model of the system before implementation. Moreover, the above-discussed tuning methods give a fixed value of gain parameters. After that with advancements in technology, various optimization techniques were applied which after performing n number of iteration provides an optimal solution for the given problem. Different controllers were designed such as optimal order PID controller for a Maglev system where both integer-order and fractional-order PID controllers were designed for a linearized model of magnetic levitation system [5]. A second-order sliding mode controller was also designed for stabilization and disturbance rejection from magnetic levitation system [6]. Another optimization technique that is Grey wolf optimization was also used to design an optimal PID controller to improve the performance index of the system by minimizing the steady-state error [7]. Both time domain and frequency domain specifications of the system can be improved by the performance index minimization using teaching-learning based optimization technique for tuning of PID controller gain values [8]. While working with optimal PID controllers there should be prior knowledge of different linearization methods namely Taylor series, analytic linearization approach, and feedback linearization method. A complete mathematical model of the system is also required before applying linearization methods. One more optimal controller that is a Linear Quadratic Regulator (LQR) along with PID was implemented on a maglev system to enhance the transient performance and stability of the system [9]. This again was having the disadvantage of thorough knowledge of mathematical modelling of the system along with deciding of weights of Q and R system matrix as and when any system parameter changes. In all cases, the output produced from the magnetic levitation systemexhibits considerable overshoot in the response. So a high-performance nonlinear controller was designed to remove overshoot from the system by changing the damping ratio of the system [10]. These problems were further solved by implementation of artificial intelligence to the given system and then intelligent controllers were designed. Intelligent controllers include fuzzy logic controller, neural networks, neuro-fuzzy controllers, genetic control [11]. Fuzzy controllers do not require the complete modelling of the system and simple to implement since it works only with linguistic variables. Fuzzy controllers were used to enhancing the performance index and stability of the system and results were compared with classical and optimal controller [12]. Working on fuzzy controllers requires the knowledge of deciding on linguistic variables, range of input/output parameters as well as forming the rules to deal with the control problem. It is also presented by some authors that it is possible to increase the levitation force by using superconductors to produce the levitation force. Even if the system is not optimized still considerable outputs are produced by using superconducting levitation [13].

In this paper, a simplified optimal controller is designed using particle swarm optimization technique to optimize the PID gain values. The performance parameters of PID controller when tested on hardware were poor so to enhance the quality of PID controllers certain intelligent algorithms such as particle swarm optimization (PSO) are incorporated to find the optimal values of tuning parameters. PID along with PSO is easy to implement and provides good computational efficiency [14]. Particle swarm optimization (PSO) technique was explained by Kennedy and Eberhart in 1995 [7]. PSO algorithm was developed by observing the physical nature of birds and fishes in a group. Particle swarm optimization is based on updating the best solution again and again and its particles can memorize its best solution. This is a continuous process and as the best solution is approached every particle starts moving in that direction. Now the PSO has been applied in many fields to solve many optimization problems such as system identification, function optimization, artificial neural network training etc. Here PSO technique is applied to a non-linear magnetic levitation system which requires the model description and modelling as explained in the next section.

This paper is organized in the following manner: Section I comprises of introduction of system, followed by description and dynamic model analysis of Maglev within Section II. Section III consists of the control techniques and implementation of PID and PSO tuned PID controllers. In Section IV, experimental analysis is discussed while Section V presents a detailed explanation of results and stability comparison. Finally, conclusions are drawn in Section VI.

II. MAGNETIC LEVITATION SYSTEM DESCRIPTION

A. *Description of Maglev System*

The laboratory-based Maglev system consists of an electromagnetic coil, a metal sphere ball, an IR sensor, power supply and heat sink as shown in Fig.1. The hardware setup that is used here for experimental analysis is a 33-210 magnetic levitation mechanical unit setup by Feedback Instruments Limited [15]. Along with magnetic levitation system, the mechanical unit used a 33-301 analog interface control have also used and a PCI1711 card that is installed inside the computer and used to convert the signals coming from the simulated controller in MATLAB to the signals that can be easily sensed by the hardware model [15]. Maglev system can be considered having two subsystems that are electrical and mechanical. The magnetic levitation system serves to make the small metal ball levitate in the air at some equilibrium position [3]. Sufficient amount of electric current is passed through the electromagnet to produce an adequate amount of magnetic force to support the ball's weight. The ball position is controlled by regulating the amount of current passing through the electromagnetic coil. The current through the coil is controlled by controlling the voltage applied on the electromagnet terminals. The applied voltage indirectly controls the position of the ball [5]. Magnetic levitation system is nonlinear and inherently unstable. For a stable levitation of metal ball in the air space, the magnetic levitation system should be linearized and the gravitational force must be balanced by an equal magnetic force as explained in the next section.

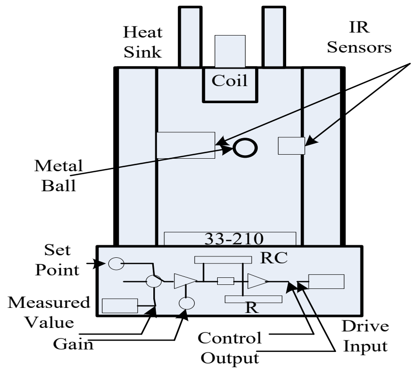

Fig.1 Laboratory-based Magnetic Levitation System setup

B. *Dynamic Model Analysis*

The schematic diagram of the single axis Maglev system is illustrated in Fig.2. It consists of an electromagnetic coil, current driver, a controller, a sensor system, analog/digital converter and a levitation object. The levitation object is a small metal ball. A light source and light receiver are used as a sensor system to detect the position of the levitating ball. The current passing through the Maglev system produces a sufficient amount of magnetic force to equalize the gravitational attraction acting on the ball and thus the position of the ball is controlled in the air space. The position of the ball is fed back to the controller through the receiver action thus the amount of current passing through the electromagnetic coil is regulated. The attraction force on the levitating ball is controlled by the currents of the current driver which is computed by the controller.

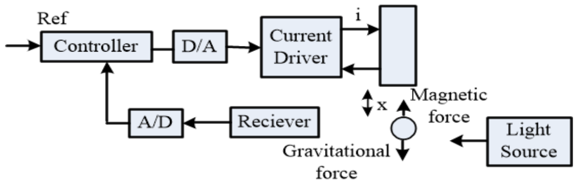

Fig.2 Schematic Diagram of Maglev system

The magnetic force produced by electromagnet should be equal and opposite of the gravitational force acting on the metallic ball to make the ball levitate in the air. The magnetic force depends on the distance between the metal ball and electromagnetic coil, the current passing through the electromagnetic coil and the electromagnet characteristics [16].

The motion of the metal ball under the influence of gravitational and magnetic force is expressed as:

$$m\ddot{x} = mg - f_e \quad (1)$$

where, f_e = magnetic force m = mass of the ball, x = position of ball and g = acceleration due to gravity

Electrical power input to a conservative system:

$$P_e = vi = i\frac{d\lambda}{dt} \quad (2)$$

The mechanical power output of the system:

$$P_m = f_e \frac{dx}{dt} \quad (3)$$

Rate of change of energy stored in the system:

$$f_e = \frac{ki^2}{x^2} \quad (4)$$

where k depends on system parameters.

$$m\ddot{x} = mg - \frac{ki^2}{x^2} \quad (5)$$

The magnetic force (f_e) produced is directly proportional to the current in the coil (i) and inversely proportional to the distance of ball (x) from the electromagnetic coil.

Linearizing state characteristic equation of the system at i_o and x_o

$$\ddot{x} = F(x,\ i)$$

$$\ddot{x} = \frac{1}{m}[\frac{\partial}{\partial i}(mg - \frac{ki^2}{x^2})\ \Delta i + \frac{\partial}{\partial x}(mg - \frac{ki^2}{x^2})\ \Delta x] \quad (6)$$

$$\ddot{x} = \frac{-2ki_o}{mx_o{}^2}\Delta i + \frac{2ki_o{}^2}{mx_o{}^3}\Delta x \quad (7)$$

At equilibrium:

$$g - \frac{ki_o{}^2}{mx_o{}^2} = 0 \quad (8)$$

$$g = \frac{ki_o{}^2}{mx_o{}^2} \quad (9)$$

$$\ddot{x} = \frac{-2g}{i_o}\Delta i + \frac{2g}{x_o}\Delta x$$

Taking, $\frac{-2g}{i_o}$ = ki and $\frac{2g}{x_o}$ = kx (10)

$$\ddot{x} = -ki\Delta i - kx\Delta x \quad (11)$$

Taking Laplace Transform

$$s^2\Delta X = -ki\Delta I - kx\Delta X \quad (12)$$

$$(s^2 + kx)\Delta X = -ki\Delta I \quad (13)$$

$$\frac{\Delta X}{\Delta I} = \frac{-ki}{s^2 + kx} \quad (14)$$

By substituting equilibrium point values i_o= 0.8A an x_o = -1.5V (0.009m)

$$G(s) = \frac{-24.525}{s^2 - 2180} \quad (15)$$

There is an internal circuit provided in the Maglev system to develop a relationship between the voltage and current.
i= 1.05 *v

The output from the sensor is given as:

$$x_v = 143.48x_m - 2.8 \quad (16)$$

where, x_m = actual position in meter

Magnetic levitation plant consists of voltage to position converters to convert the control input voltage to the ball position and it is given by equation (16). Control strategies to control the position of levitating ball in the air are described in the next section.

III. CONTROL TECHNIQUES

In this section controllers are designed for desired path trajectory tracking and position control of metal ball in air for Maglev system. The most common is a PID controller that is also called a classical controller. In this paper the PID gain values are optimized using particle PSO technique. The different control techniques that are PID, PSO and PSO PID have explained in detail below.

A. Proportional Integral and Derivative (PID) Controller

The conventional PID controllers are very popular since 1900 and find usage and many industrial applications. All processes find their base of controlling from PID controller only. For a PID controller the equation for transfer function is given as:

$$T_{PID} = (K_P + \frac{1}{s}\ K_i + sK_D)\ E(s)$$

where K_P, K_i and K_D are proportional, integral and derivative gain respectively. E is the error of system and T_{PID} is the output of the controller. The tuning parameters of the PID controller are calculated using the Z-N method. Z-N method has an advantage that it is very simple to use with a simple formula based tuning parameters but it also comes with a disadvantage that controller settings require aggressive changes resulting in large overshoot and oscillatory responses for processes having a prominent delay.

B. Particle Swarm Optimization (PSO)

Eberhart and Kennedy introduced particle swarm optimization (PSO) as an uncertain search method for functions optimization [17]. Particle swarm optimization technique is a stochastic method suitable for continuous-variable problems. It is inspired by social behavior and movement of birds and fishes in a group. In PSO, particles flow in the search space and follow each other. Each particle memorizes its position and moves in the search space in the influence of its neighbors. Particles learn from each other and move closer to the best neighbor. Each particle takes up its best position according to the best place available in the entire neighborhood [17]. This algorithm is very simple to implement and deal with very few parameters. Particle swarm optimization is applied to numerous areas in optimization and with other existing optimization algorithms. This method searches for an optimal solution with the help of particles whose trajectories are adjusted by a deterministic component. Each particle is optimized by its best-achieved position through the iterative approach. A particle i is taken, whose position and velocity vector are defined as x_i and v_i respectively. After every iteration each particle changes its position with velocity. PSO algorithm works on finding multiple potential solutions for a given problem. Each solution is represented by a particle in the fitness landscape. After every iteration, the fitness of solution is checked through an objective function. [18].

In particle swarm optimization technique, particle taken into account helps to find the best possible solution for the problem by calculating a fitness function. The velocity of each particle controls its motion in the search space. An optimal solution is generated by updating the position of particles again and again [17]. Particles work on achieving two best values, (pBest) the best position determined to achieve soon and the best position already achieved through iterations (gBest). The position of each particle and its velocity is updated according to equations (17) and (18) using the best values found so far.

$$v_i^{t+1} = wv_i^{t} + c_1\alpha * \left(x_i{}^{t}{}_{pBest} - x_i{}^{t}\right) + c_2\beta * (x^{t}{}_{gBest} - x_i{}^{t}) \quad (17)$$

$$x_i^{t+1} = x_i{}^{t} + v_i{}^{t+1}, i = 1,2, \ldots \ldots, n_{pop} \quad (18)$$

where x_i is the i_{th} particle position, v_i is the i_{th} particle velocity, n_{pop} is the particle swarm population, $x_{i_{pBest}}$ is the best position achieved by the particle, x_{gBest} is the best global position achieved by all particles up to generation t, w is the inertia weight, $c_1 and\ c_2$ are acceleration coefficients, α and β are uniform random numbers. The equations depict the movement of particles and changing the velocity of each particle after every iteration. Particles move towards the best position achieved by any particle in the search space and thus results to give an optimized solution. Table I represents the PSO parameters that are chosen for the given system.

Table I PSO Parameters

Parameter	Values
Members of each individual	K_p, K_i
K_D	0.2
Maximum iteration	50
Population size (n_{pop})	50
c_1	2.0
c_2	2.0
w	0.9

C. PSO PID Controller

The gain parameter values of the PID controller are optimized using PSO algorithm. The new gain parameter values are adapted based on the fitness function selected for the given plant. For PID controller a three-dimensional search space is chosen of the PID gain parameters that are K_P, K_i and K_D. The particle size and number of iterations are decided based on the requirement. The fitness function calculates the performance of the plant in each iteration and the best value is chosen by particles among all the calculated values of fitness.

Particle swarm optimization is a social search method and the steps required to implement PSO algorithm are, first, the group of particles are chosen randomly and the optimal solution is found by updating the generations. The iterations are continually performed till pBest values is obtained and the value for the best position is updated again and again to generate the gBest value. The position and velocity of each particle are updated in one-dimensional space. The best particle gets fixed in one place and other particle starts moving towards it. Once the global best position is obtained algorithm meets its termination criterion and the optimization algorithm stops after updating the best position globally.

IV. EXPERIMENTAL ANALYSIS

A PSO tuned PID controller was designer in this paper for controlling the ball levitation in air. When current passes through the electromagnetic coil and sufficient magnetic force is produced the magnetic ball gets attracted towards it, otherwise, a ball falls due to gravitational force. The ball position is sensed with the help of an IR sensor. The aim here is to control the ball levitation in air and make it move along a fixed path trajectory.

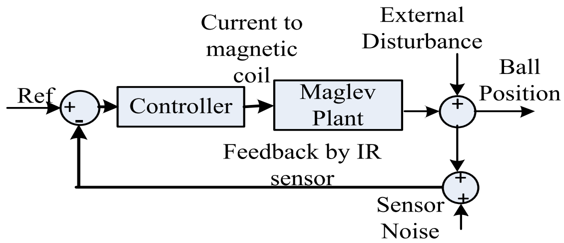

Fig.3 Block Diagram of Maglev System with the controller

Magnetic levitation system with a controller is shown with the help of a block diagram in Fig.3. As shown a reference trajectory (step input, square wave input or sine wave input) is given to the controller and it is compared with the output of feedback sensor and a control signal is generated to make the metal ball levitate and follow the given reference trajectory. Since the aim is not only to control the ball levitation but also to track the desired reference trajectory so, optimization should be performed until desired controller parameters are achieved. The maglev plant consists of voltage to position converters to convert the control voltage signal to a position as given by equation (16) so that trajectory can be observed and feedback generated can be compared with the reference trajectory by the controller.

A. Implementation of PID and PSO tuned PID controller

For controlling the ball levitation in the air a sufficient amount of magnetic force must be produced. For this purpose, PID and PSO PID controllers are designed.

There are three parameters to be controlled while designing the PID controller that are K_p, K_i and K_D. These parameters are tuned using the Z-N method and the gain values K_p, K_i and K_D are determined as given in Table II.

Table II PID Gain values

Controller	K_p	K_i	K_D
Gain values	4	0	0.2

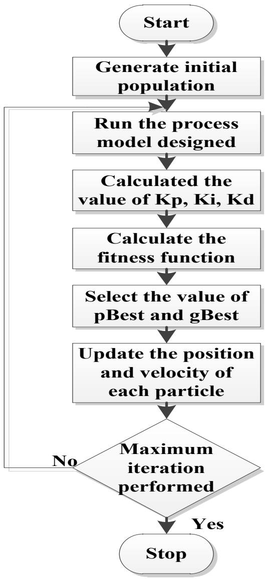

Fig.4 Flow chart of PSO algorithm

The stepwise implementation of PSO algorithm on the Maglev system is shown in Fig.4. For designing a suitable PSO PID controller for magnetic levitation system number of experiments were performed in MATLAB with a population of 50 and maximum 10 iterations were performed to obtain the gain parameter values.

These PSO tuned PID controller gain values are determined by obtaining the transfer function of the maglev plant by dynamic model analysis of the system. The particle swarm optimization parameters are depicted in Table I and based on these values an algorithm is generated based on the given transfer function to design an optimized controller. Gain values of PSO tuned PID controller are given in Table III. The PSO optimization algorithm is used in offline mode and the iterations were performed continuously till optimized value for better system performance parameters were obtained.

Table III PSO PID Gain values

Controller	K_p	K_i	K_D
Gain values	4.0214	1.777	0.2000

V. RESULTS AND DISCUSSION

A. Simulation Results

The study of the Maglev system for different controller designs has been done by implementing PID and PSO PID controller using MATLAB/SIMULINK. A step input trajectory of the initial and final value of 0.009 and 0.0055 respectively has been given to the system. The response for magnetic levitation system after the implementation of PID and PSO tuned PID controllers are discussed in Fig.5 using SIMULINK. It is observed from the graph that the output from PID controller does not match the reference step wave trajectory and thus produces a large steady-state error as compared to the output trajectory that is obtained by PSO PID controller. Initially, a step input of amplitude 0.015 is given for a time duration of 5 seconds and the results were analyzed for both PID and PSO PID controller for the given duration. The results show that the ball movement in air varies from 0 mm to 0.0125 mm while using PID controller. The response does not coincide with the reference trajectory due to which a large amount of steady-state error existed for ball position movement in Maglev system. While using PSO PID controller the ball position in air varies from 0 mm to 0.010 mm within initial 5 seconds and the ball settles with the desired reference trajectory at 3 seconds and the response follows the desired trajectory. It can be seen from Fig.5, that the peak overshoot with a PID controller for the ball position movement is more than PSO PID controller. Table IV represents the comparative time response analysis of implemented controllers for Maglev system.

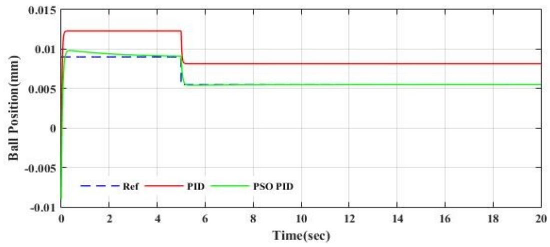

Fig.5 Step input response of Maglev system using SIMULINK

Table IV Time Response Analysis using SIMULINK

Controller	Peak Time	Settling Time	Steady State Error
PID Controller	0.7900	---	23.63%
PSO PID Controller	0.3600	3.12	12%

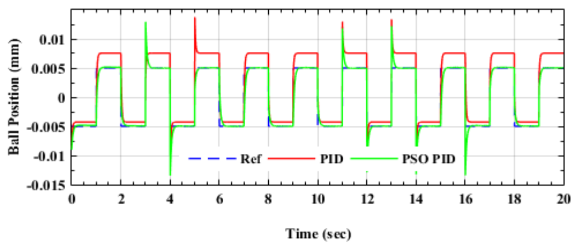

Fig.6 Square wave response of magnetic levitation system using SIMULINK

From the time response analysis, it is observed that the steady-state error, peak time and settling time of the system are minimum in case of PSO PID controller which are 0.36 sec, 5.02 sec and 12% respectively from Table IV.

A square wave trajectory of 0.5Hz with an amplitude of 0.005 has been considered to observe the output generated when square wave input is given to the magnetic levitation system. It is observed that the designed PSO PID controller gives much precise output as compared to a PID controller in terms of steady-state error value as shown in Fig.6.

B. Hardware Results

The hardware model of magnetic levitation system designed by Feedback Instruments Ltd. comprises of the mechanical unit with an electromagnetic coil at top, IR sensor at opposite sides of the construction, Advantech card and an interface unit [15].

From Table V it is observed that when time response analysis is performed on hardware then settling time and steady-state error are minimum in case of PSO PID Controller i.e. 3.98 seconds and 1.32% respectively as compared to the steady error generated by implementing PID controller to magnetic levitation system.

Table V Time response analysis on real-time system

Controller	Peak Time	Settling Time	Steady State Error
PID Controller	1.25	----	25.53%
PSO PID Controller	0.22	19.8	1.32%

Response for magnetic levitation system after implementing PID and PSO PID controllers on the real-time system are discussed in Fig.7 and Fig.8 respectively. The same value of step input as given to the simulation model has been considered and the results were observed on 33-210 magnetic levitation kit. The results were analysed by time response analysis for both the system configurations with PID and PSO tuned PID controller as shown in Fig.7. While implementing the controllers on hardware, a step input of amplitude 0.015 has been given for a time duration of 15 seconds. The ball movement in air varies from 0 mm to 0.024 mm while using the PID controller and the ball shows numerous oscillations at the starting point. The ball settled to its desired trajectory at 4.02 seconds, but the response does not coincide with the reference trajectory in case of PID controller. Due to which a constant steady-state error lies in the system and ball is not able to track the desired trajectory until the end of the simulation. While using PSO PID controller, it can be observed that the ball position in air varies from 0 mm to 0.018 mm within the initial 5 seconds and the response settles at 3.98 seconds. It is observed from the output response of ball position that the peak overshoot with a PID controller is more than PSO PID controller. Further, the ball settles to its desired trajectory at 14 seconds with zero oscillations for PSO PID controller. Maglev system is more stable in terms of ball position movement with PSO PID controller as compared to the PID controller.

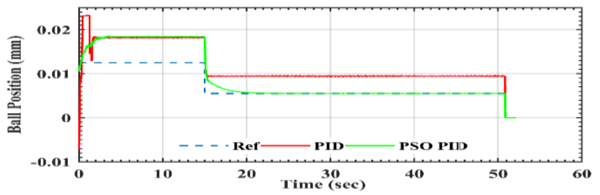

Fig.7 Step response of a magnetic levitation system in real-time

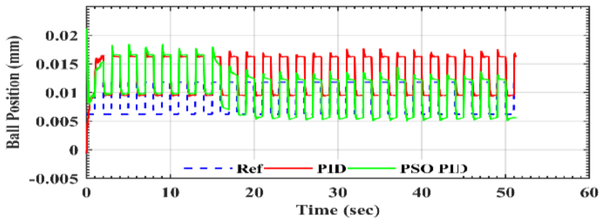

Fig.8 Square wave response of a magnetic levitation system in real-time

VI. CONCLUSION

In this paper, a PSO tuned PID controller is designed for a Maglev system with optimized gain values using particle swarm optimization technique. The transfer function of the system is developed using dynamic model analysis and a simplified mathematical model of the system is generated. The proposed optimization technique shows improvement in time domain analysis for both case when applied on SIMULINK model of magnetic levitation system as well on a real-time system. PID and PSO tuned PID controllers were designed and implemented, the results were compared and improvement is observed in terms of steady-state error and settling time of the system. The steady-state error for simulation and hardware model after implementation of PSO PID controllers is 12% and 1.32% respectively as compared to 23.63% and 25.53% after the implementation of PID controller on the same system with same parameter values. Shortly this research study can be incorporated with model uncertainties to define robustness and perform the stability analysis of the system.

REFERENCES

[1] J. R. Middala, "Modeling and Analysis of Magnetic Levitation System Using Fuzzy Logic Control," International Journal of Scientific Development and Research, Vol. 2, no. 6, pp. 318–323, 2017.

[2] S. Yadav, J. P. Tiwari, and S. K. Nagar, "Digital control of magnetic levitation system using fuzzy logic controller," International Journal of Computer Applications, Vol. 41, no. 21, pp. 22-26, 2012.

[3] P. Balko, and D. Rosinová, "Modeling of magnetic levitation system," the 21st International Conference on Process Control (PC), 2017, pp. 252-257.

[4] M. Hypiusová, and A Kozáková, "Robust PID controller design for the magnetic levitation system: frequency domain approach," the 21st International Conference on Process Control (PC), 2017, pp. 274-279.

[5] S. K. Verma, S Yadav, and S K. Nagar "Optimal fractional order PID controller for magnetic levitation system," the 39th National Systems Conference (NSC), 2015, pp. 1-5.

[6] H. K Chiang, C. C. Fang, W. B. Lin, and G. W. Chen, "Second-order sliding mode control for a magnetic levitation system," the 8th Asian Control Conference (ASCC), 2011, pp. 602-607.

[7] S. Yadav, S. K. Verma, and S. K. Nagar, "Optimized PID controller for magnetic levitation system," IFAC-PapersOnLine, vol. 49, no. 1, 2016, pp. 778–782.

[8] S. Yadav, S. K. Verma, and S. K. Nagar, "Performance enhancement of magnetic levitation system using teaching learning based optimization," Alexandria Engineering Journal, vol. 57, no. 4, pp. 2427–2433, 2018.

[9] K. Anurag, and S. Kamlu, "Design of LQR-PID controller for linearized magnetic levitation system." the 2nd International Conference on Inventive Systems and Control (ICISC), 2018, pp. 444-447.

[10] D. Khimani, S. Karnik, and M. Patil, "Implementation of High Performance Nonlinear Feedback Control on Magnetic Levitation System," IFAC-PapersOnLine, vol. 51, no. 1, 2018, pp. 13–18.

[11] R. Singh, and B. Bhushan, "Real-time control of ball balancer using neural integrated fuzzy controller," Artificial Intelligence Review, pp. 1-18, 2018.

[12] A. C. Unni, A. S. Junghare, V. Mohan, and W. Ongsakul, "PID, fuzzy and LQR controllers for magnetic levitation system," the International Conference on Cogeneration, Small Power Plants and District Energy (ICUE), 2016, pp. 1-5.

[13] P. Bernstein, L. Colson, and J. Noudem, "A New Magnetic Levitation System With an Increased Levitation Force," IEEE Transactions on Applied Superconductivity, Vol. 29, no. 5, pp. 1-4, 2019.

[14] C. M. Lin, M. H. Lin, and C. W. Chen, "SoPC-based adaptive PID control system design for magnetic levitation system," IEEE Systems Journal, Vol. 5, no. 2, pp. 278-287, 2011.

[15] M. Levitation, "MAGNETIC LEVITATION Installation & Commissioning 33-942IC,".

[16] M. Golob, and B. Tovornik. "Modeling and control of the magnetic suspension system," ISA transactions, 42, no. 1, pp. 89-100, 2003.

[17] S. M. H. Mousakazemi, and N. Ayoobian. "Robust tuned PID controller with PSO based on two-point kinetic model and adaptive disturbance rejection for a PWR-type reactor," Progress in Nuclear Energy, 111, 2019, pp. 183-194.

[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 Transactions on Industrial Electronics, Vol. 58, no. 2, pp. 629-646, 2010.