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Conference Paper · January 2015

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Design of PID and FOPID Controllers based on Bacterial Foraging and Particle Swarm Optimization for Magnetic Levitation System

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Abstract— **This paper deals with design and implementation of controllers to stabilize a ferromagnetic ball in a Magnetic Levitation (Maglev) system and control the ball position to track a reference signal within an operating region. For this purpose, PID and Fractional Order PID (FOPID) controllers have been designed using Particle Swarm Optimization (PSO), Bacterial Foraging (BF) optimization, and Bacterial Foraging oriented by PSO (BF-PSO) optimization algorithms. The PID and FOPID controllers are implemented in the Maglev system of Feedback Instruments (Model No 33-210) and tested with step change, sine wave and square wave as reference signals. Transient and steady state responses are found to be satisfactory. The results reveal that BF-PSO provides better tuning algorithm than individual BF and PSO algorithm. Further, FOPID works better than PID, with BF-PSO tuning approach.**

I. INTRODUCTION

A. Basic principle of Magnetic Levitation (Maglev) system

In a Maglev system electromagnetic field is used to levitate a ferromagnetic object and control its position against gravity and other physical forces. Maglev technology has a great significance because it helps to eliminate frictional losses due to mechanical contact. Engineering applications of Maglev system include high-speed trains, magnetic bearings, high-precision platforms etc. Based on the difference between desired and actual positions of the object, a controller is designed to control current through electromagnetic coil to generate required force to control the position[1].

B. PID and FOPID Controller

Controllers used in this paper are PID and FOPID. In spite of advanced controllers, PID controller has remained widely used controller in industrial control applications. It is because of its simplicity to design and implement, cost effectiveness, and acceptable robustness. Although the existing techniques to design PID controller perform well, a possibility of further improvement of PID controllers is to use FOPID controller with non-integer derivative and integration parts. This is because fractional calculus has shown its potential to improve the system performance in recent years [2].

C. Literature Review

Apart from conventional controllers like PID [3], many intelligent control schemes like modified PSO [4], fuzzy logic [5], [6], neural adaptive control [7] are used in Maglev system. Advanced control techniques like feedback linearization [8], sliding mode control [9], back-stepping control [9], [10], H infinity control [11], quantitate feedback theory [12], FOPID control [13], etc. are also used. However, the survey is not an exhaustive one. Literature review has shown that fractional order controllers are relatively less explored in Maglev system. This paper focuses on how FOPID controller tuned by BF-PSO performs better for Maglev system.

D. PSO, BF and BF-PSO

The basic PSO was introduced by J. Kennedy and R. C. Eberhart in 1995 and later modified by Y. Shi and R. C. Eberhart in 1998. It was developed based on research on swarm such as fish shoaling and bird flocking [14], [15]. Many researchers used modified version of PSO for optimization in recent years[16], [17], [18]. BF optimization algorithm was introduced by K. M. Passino in 2002 [19]. This metaheuristic algorithm was developed based on behavior of E. Coli bacteria which normally lives inside intestines. In recent past, BF optimization algorithm has shown a great potential in optimal control system design[20]. In [20], BF-PSO algorithm is proposed combining PSO and BF techniques and applied for PID parameters tuning for a set of test plants in order to make use of the ability of PSO to exchange social information and ability of BF to find a new solution by elimination and dispersal. It establishes greater potential of BF-PSO over BF and PSO. Moreover, due to complex dynamics of fractional order controller, designing FOPID by classical method is a challenging task. The PSO, BF, and BF-PSO do not require to analyze the dynamics of the controller and plant. These optimization algorithms only search for suitable values of controller parameters so that a performance index (PI) is minimized. The PI is a measure of controller performance. It is generally a function of error signal.

II. MAGLEV SYSTEM DESCRIPTION

Fig. 1 shows basic setup of the Maglev system manufactured by Feedback Instruments (Model No 33-210). The system mainly consists of an optoelectronic position sensor, electromagnetic actuator coil and a suspended ferromagnetic ball. A desktop computer is connected to the system through Advantech card. MATLAB and Simulink environment is used to generate control unit. Optoelectronic sensor determines vertical position of the ferromagnetic ball and passes it to controller through Advantech card. Based on the difference between desired and measured output, controller sends current to the actuator. Actuator consists of an electromagnet formed by wrapping copper wire of 2850 turns on a high permeability cylindrical iron core. The magnetic field of coil generates upward attractive force on the ferromagnetic ball to levitate it against gravity. A suitable controller is needed to be designed to adjust current through the actuator to stabilize the levitated ball and to make it follow a reference trajectory. The levitated object is a hollow ball with mass of 20 g and diameter of 50 mm [3].

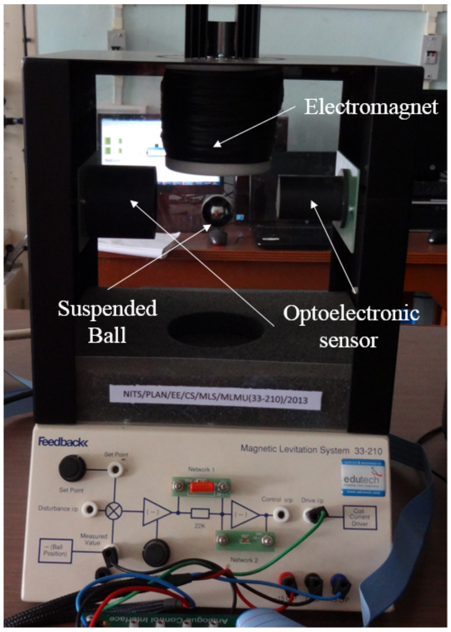

Fig. 1. Magnetic Levitation system (Feedback 33-210)

III. MODELLING BY SYSTEM IDENTIFICATION

Modelling of a system is the first and crucial step for design of a controller. Here modelling is carried out by system identification. Maglev system is open loop unstable. Hence it has been identified by close loop identification. Identification is carried out in the similar line as given in [3]. In [3], a PD controller is used to stabilize the plant as given in Fig. 2. A random signal $\left(r(t) \in (-1,1)\right)$ has been chosen as excitation input. Using $r(t)$ and output $y(t)$, close loop transfer function $T(s)$ has been found using MATLAB System Identification Toolbox. From block diagram of Fig. 2

$$T(s) = \left(\frac{Y(s)}{R(s)}\right)_{y_d=0} = \frac{G(s)}{1+C(s)G(s)} \tag{1}$$

where $C(s) = -(4+0.2s)$ and

$$T(s) = \frac{-70.4321}{s^2+14.09s+237.5}$$

. $G(s)$ is computed from (1) and shown in (2). $G(s)$ is validated using a different set of data and found 93.43% fit.

$$G(s) = \frac{-70.4321}{(s+6.653)(s-6.653)} \tag{2}$$

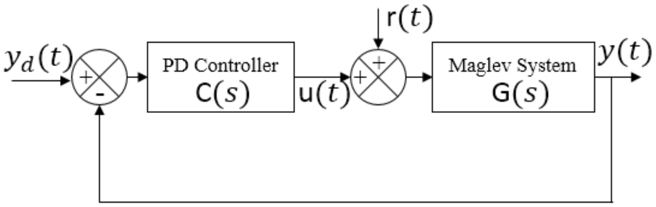

Fig. 2. System with PD controller

IV. DESIGN AND IMPLEMENTATION OF CONTROLLERS

A. PID and FOPID Controller dynamics

The dynamic equations of PID and FOPID controller are given in (3) and (4) respectively with usual notations. The parameter λ and μ stands for the order of integration and derivative respectively.

$$K_P e(t) + K_I \int_0^t e(t)\,dt + K_D \frac{de(t)}{dt} = u(t) \tag{3}$$

$$K_P e(t) + K_I D^{-\lambda} e(t) + K_D D^{\mu} e(t) = u(t) \tag{4}$$

B. Performance Index of Controller

Performance index is a quantitative measure to test the performance of a controller. For a PID or FOPID controlled system, there are often few indices like ISE, IAE, ITAE, ITSE, etc. are used. In this paper, ISE has been taken as performance index, which is given in (5), for all optimization algorithms.

$$J = ISE = \int_0^\infty e^2(t)\,dt \tag{5}$$

C. Tuning of PID and FOPID Controllers using PSO

The objective in PSO-based optimization is to find a set of PID and FOPID parameters such that performance index is minimized. Individuals are called as particles in PSO. The members of each particle are K_P, K_I and K_D for PID and K_P, K_I, K_D, λ and μ for FOPID. A particle represents a potential solution of a problem. Velocity $v_i(t)$ and position $x_i(t)$ of particles are updated according to (6) and (7) respectively. Particles' new velocity is calculated based on its previous velocity and the distances of its current position from its own best experience $x_{pi}(t)$ and the groups best experience $x_{Gb}(t)$ to determine the next direction of search, thereby narrowing the search space [14], [15], [20].

$$\begin{aligned} v_i(t+1) = w.v_i(t) + c_1.rand().(x_{pi}(t) - x_i(t)) \\ +c_2.rand().(x_{Gb}(t) - x_i(t)) \end{aligned} \tag{6}$$

$$x_i(t+1) = x_i(t) + v_i(t+1) \tag{7}$$

The function $rand()$ generates a uniformly distributed

TABLE I
PSO PARAMETERS

Number of Swarm = 50	$w = 0.9$	$c_1 = 1.2$	$c_2 = 0.2$

TABLE II

CONTROLLER PARAMETERS OBTAINED BY PSO

Controller	K_P	K_I	K_D	λ	μ
PID	4.9656	9.4912	0.1765	$---$	$---$
FOPID	4.4178	2.4697	0.1727	0.4999	0.4996

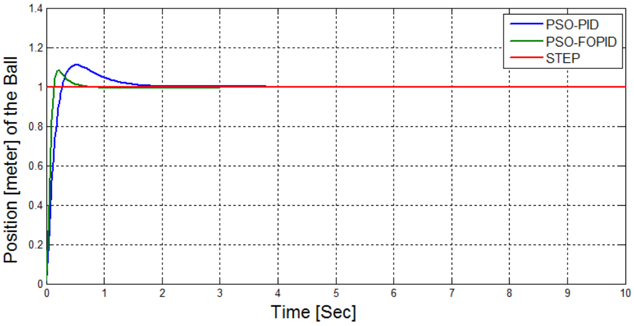

Fig. 3. Simulated step responses using PID and FOPID tuned by PSO

random number between 0 and 1. The inertia constant w takes care of local and global search. Constants c_1 and c_2 represent cognition and social acceleration constants respectively. Constants w is varied in range (0,1) c_1 and c_2 are varied in range (0,2) and best values are given in Table I. However effect of variation of w, c_1 and c_2 on the results is beyond the scope of this paper. Position $x_i(t)$ represents the controller parameters. Fitness function used to update $x_i(t)$ and $v_i(t)$ is given in (5). The iteration is continued until there is no significant changes in the fitness value for 100 consecutive iterations. The optimized controller parameters are listed in Table II. Step responses of the system using PID and FOPID tuned by PSO are shown in Fig. 3.

D. Tuning of PID and FOPID Controllers using BF

The selection behavior of bacteria tends to eliminate poor foraging strategies and improve successful foraging strategies. This activity of foraging led the researchers to use it as an optimization process. BF algorithm may be described in the flow chart as shown Fig. 4 [19], [20]. The BF initialization parameters are given in Table III and controller parameters obtained are listed in Table IV. Step responses of the system using PID and FOPID tuned by BF are shown in Fig. 5.

TABLE III

BF PARAMETERS

Dimension of search space (N)	3 (PID) , 5 (FOPID)
Population size $(s) = 10$	Chemo-tactic steps $(N_c) = 5$
Length of a swim $(N_s) = 4$	Reproduction steps $(N_{re}) = 4$
Elimination-dispersal $(N_{ed}) = 2$	Reproductions rate $(S_r) = s/2$
Elimination probability of each bacteria $(P_{ed}) = 0.2$	

TABLE IV

CONTROLLER PARAMETERS OBTAINED BY BF

Controller	K_P	K_I	K_D	λ	μ
PID	4.9782	1.799	0.2283	$---$	$---$
FOPID	3.9244	2.0114	0.1662	0.0715	0.1955

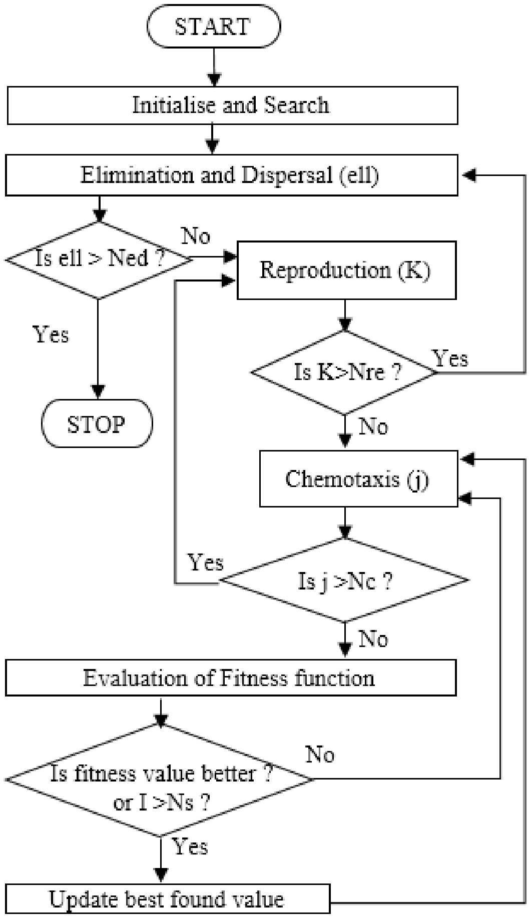

Fig. 4. Flow chart for BF Optimization Algorithm

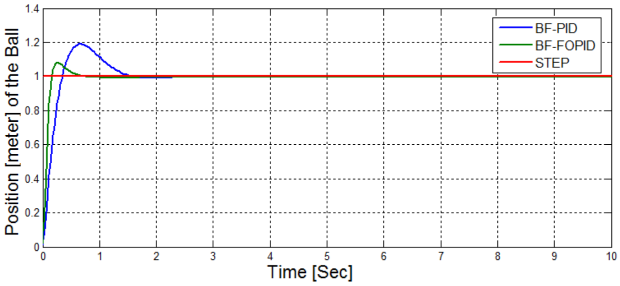

Fig. 5. Simulated step responses using PID and FOPID tuned by BF

E. Tuning of PID and FOPID Controller using BF-PSO

The BF-PSO algorithm includes BF Optimization oriented by PSO. BF-PSO algorithm is described by a flow chart given in Fig. 6 [20]. The same initialization parameters of BF and PSO are used in BF-PSO except $P_{ed} = 0.25$. Iteration is continued until there is no significant changes in the fitness value for 100 consecutive iterations. Optimized controller parameters are shown in Table V. Step responses using PID and FOPID tuned by BF-PSO are shown in Fig. 7.

TABLE V

CONTROLLER PARAMETERS OBTAINED BY BF-PSO

Controller	K_P	K_I	K_D	λ	μ
PID	3.5793	9.5924	0.3339	− − −	− − −
FOPID	4.8782	2.1375	0.3643	0.5001	0.5022

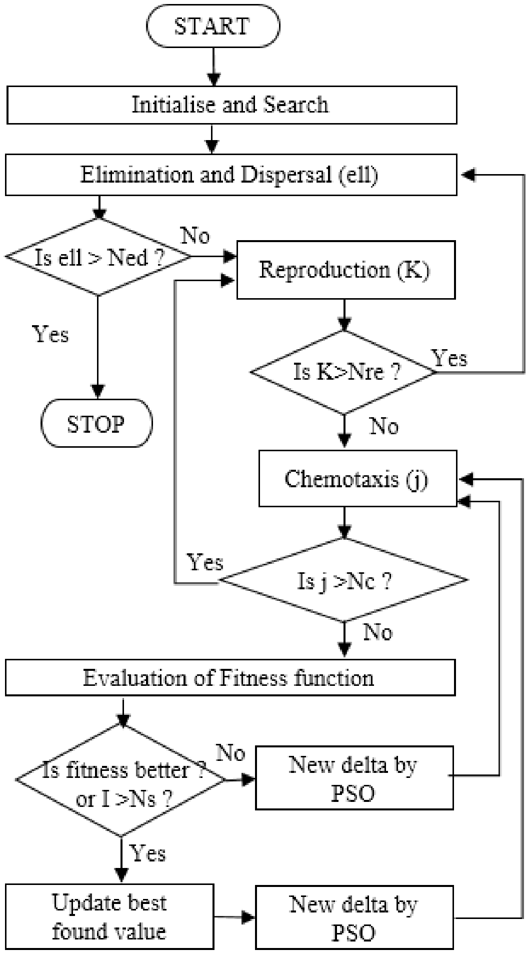

Fig. 6. Flow chart for BFPSO Optimization Algorithm

F. Implementation of proposed controllers in real system

The proposed PID and FOPID controllers are implemented through MATLAB and Simulink environment of desktop computer. FOPID controller is realized by Fractional Order Modelling and Control Toolbox (FOMCON) inside Simulink environment. Because of inherently unstable nature of the system, integral action is turned on after 15 seconds. To take care of negative gain of the plant, output of the controller is inverted and then applied to the plant. Real time results are shown in Fig. 8 to Fig.19.

V. RESULTS AND DISCUSSIONS

Among step responses shown in Fig. 3, 5, and Fig. 7, FOPID tuned by BF-PSO shows the best result (overshoot 0.528% and settling time 0.327 sec). Real time results in Fig. 8 to Fig. 19 indicate that controllers tuned by BF-PSO perform better than that of BF and PSO individually. Results

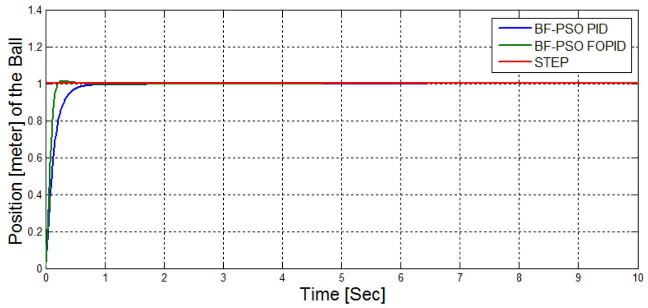

Fig. 7. Simulated step responses using PID and FOPID tuned by BF-PSO

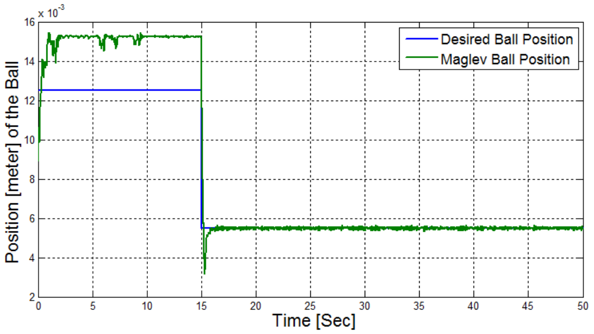

Fig. 8. Real time system response with PID tuned by PSO using step change as reference input (only PD during 1st 15 sec)

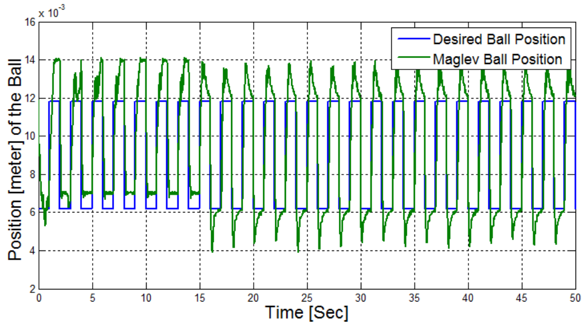

Fig. 9. Real time system response with PID tuned by PSO using square wave as reference input (only PD during 1st 15 sec)

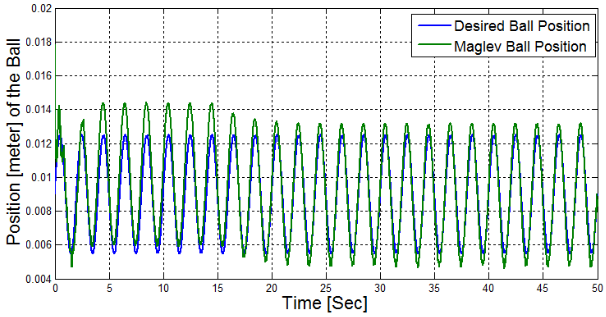

Fig. 10. Real time system response with PID tuned by PSO using sine wave as reference input (only PD during 1st 15 sec)

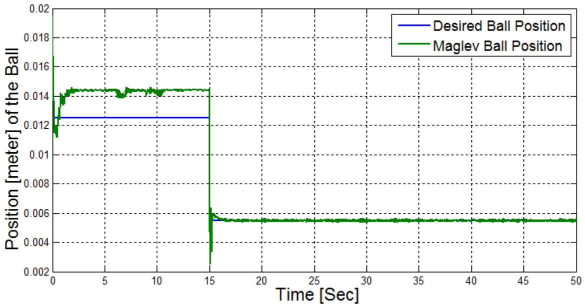

Fig. 11. Real time system response with PID tuned by BF with step change as reference input (only PD during 1st 15 sec)

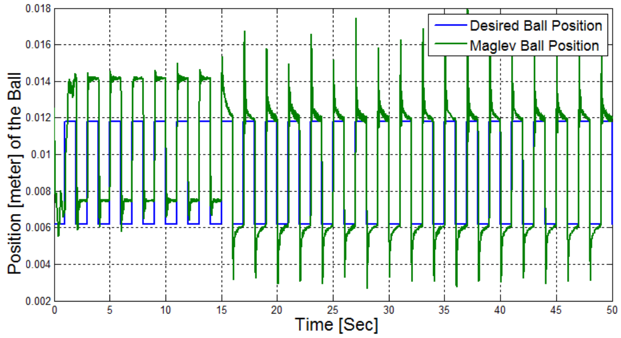

Fig. 12. Real time system response with PID tuned by BF using square wave as reference input (only PD during 1st 15 sec)

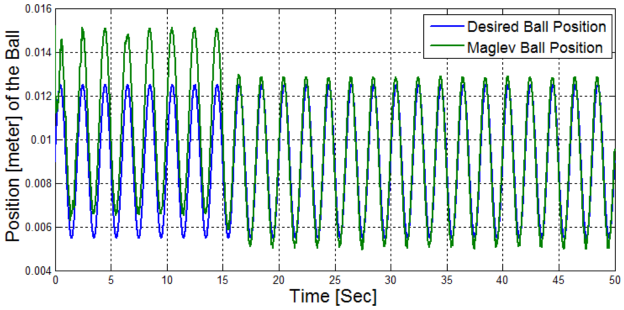

Fig. 13. Real time system response with PID tuned by BF using sine wave as reference input (only PD during 1st 15 sec)

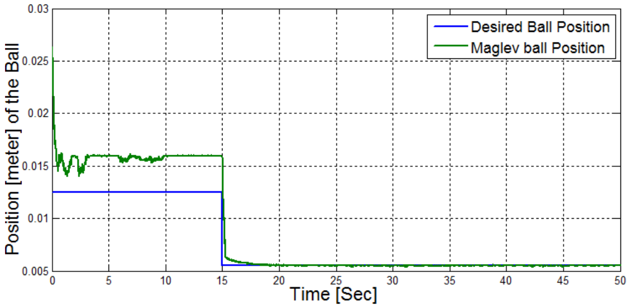

Fig. 14. Real time response with PID tuned by BF-PSO using step change as reference input (only PD during 1st 15 sec)

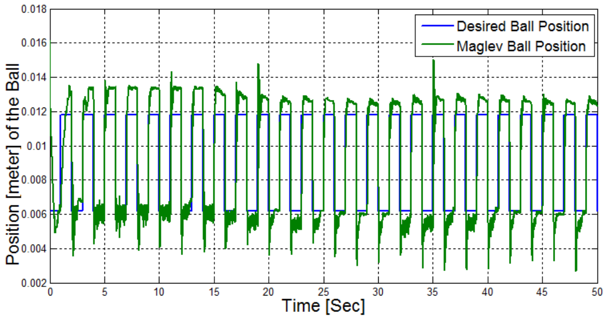

Fig. 15. Real time response with PID tuned by BF-PSO using square wave as reference input (only PD during 1st 15 sec)

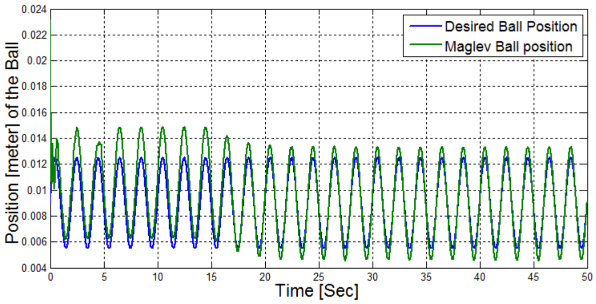

Fig. 16. Real time response with PID tuned by BF-PSO using sine wave signal as reference input (only PD during 1st 15 sec)

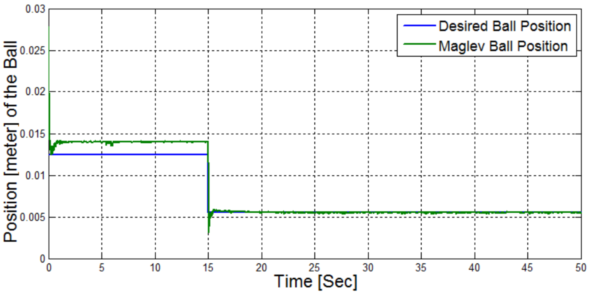

Fig. 17. Real time response with FOPID tuned by BF-PSO with step change as reference input (only FOPD during 1st 15 sec)

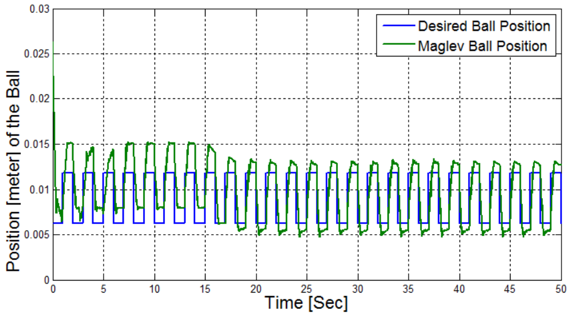

Fig. 18. Real time response with FOPID tuned by BF-PSO using square wave as reference input (only FOPD during 1st 15 sec)

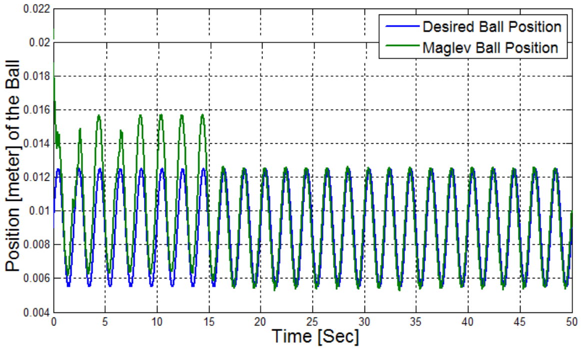

Fig. 19. Real time response with FOPID tuned by BF-PSO using sine wave as reference input (only FOPD during 1st 15 sec)

also show that FOPID tuned by BF-PSO is working better than all other controllers considered in this paper in terms of tracking of a reference signal. Feedback Maglev 33-210 model being new, has little research work done on it. Hence, comparisons have been done mostly with similar contemporary set ups. Literatures with only simulation results have not been compared. Results in this paper are better than [9] and the system inbuilt PID controller [3] in terms of tracking of a reference signal. In [8], results show transient and steady state behaviors similar to this paper but it shows chattered behavior during initial 0.3 seconds. Back stepping and high gain observer based controller in [10] has higher overshoot (12%) and settling time (3.5 sec) than this paper. H∞ controller in [11] gives less settling time but higher overshoot (4%) and the steady state error is not completely zero. QFT controller in [12] gives settling time nearly 1 sec which is higher compared to this paper. In [13], a fractional order PID controller is designed by minimizing ISE, IAE, ITSE, MCE etc. by classical optimization method. But real time results in [13] contains higher overshoot (10 to 15% in various cases) and settling time (8 to 10 sec. in various cases) than this paper.

VI. CONCLUSIONS AND FUTURE SCOPE

In this paper PID and FOPID controllers are designed using PSO, BF, and BF-PSO algorithms for Maglev system. Performances are compared. Tuning of FOPID controller is a difficult task especially for nonlinear and inherently unstable plant. Results justify that BF-PSO algorithm is a suitable tool to tune the FOPID controller parameters in Maglev system. Results also justify greater potential of FOPID controllers over the corresponding PID controllers. Comparisons with contemporary literatures show that the proposed method has better performance over existing controllers. The future work will focus to run the device as a standalone system without the use of a computer. Step change, square wave, and sine wave are used as reference signals in this paper. A complex reference signal may be used in future. Modelling of Maglev system by a fractional order transfer function will also be attempted in future.

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