

Iterative Learning Control Based Fractional Order PID Controller for Magnetic Levitation System

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ABSTRACT

Maglev (Magnetic Levitation) systems are an interesting class of systems since they work without any physical contact and are hence frictionless. Due to this attractive property, such systems have the potential for wide range of applications such as maglev trains. Maglev is non-linear due to magnetic field and unstable that suggest the need of stabilizing controller. An appropriate controller is required to levitate the object at desired position. FOPID (Fractional Order Proportional Integral Derivative) controller and ILC (Iterative learning Control) based FOPID controller are designed in this paper for the levitation of metallic ball with desired reference at minimum transient errors. Since maglev is unstable and ILC is used only for stable systems, FOPID controller is used to stabilize the plant. Non-linear interior point optimization method is used to obtain the parameters of FOPID controller. An ILC is used as a feedforward controller in order to improve the response iteratively. P, PD and PID-ILC control laws are used to update the new control input in ILC based FOPID controller. The overall control scheme is therefore a hybrid combination of ILC and FOPID. The effectiveness of proposed technique is analyzed based on performance indices via simulation. ISE (Integral Square Error) and IAE (Integral Absolute Error) is lesser in case of hybrid PID-ILC as compared to simple FOPID controller.

Key Words: Magnetic Levitation System, Fractional Order PID Controller, Hybrid, Iterative Learning Controller.

1. INTRODUCTION

Maglev is a non-contact system. An object is levitated through this system without any human interaction through magnetic force generated by an electromagnetic coil. This type of process offers many real-world applications, for example: magnetic bearings, artificial blood pumps, suspension of wind models and transportation systems [1]. Because of such applications, these systems have been getting increasing attention [2]. Maglev has many advantages.

These systems are frictionless and work with low noise for accurate positioning [3]. Because of their non-contact nature, Maglev system moderates the cost of maintenance and the energy efficiency of these system is high [4].

An electromagnetic coil is fixed in Maglev on the top of the box and sensor is located on the opposite side of this box which senses the position of the ball. When voltage

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is applied to the electromagnet, the current is induced. This current magnetizes the coil and applies a magnetic force on the ball. When this magnetic force and force of gravity become equal then this ball is suspended at desired position [5].

In theory, it looks very simple to find out “how much is the force on the ball at a specific point”, but it is not possible to levitate the object (ball) at desired position in the absence of an appropriate controller. Maglev is highly non-linear and inherently an unstable plant, described by non-linear differential equations [6]. A real-time controller is necessary to stabilize the system and levitate the object at desired position. This real-time controller will keep the two forces (gravitational force and electromagnetic force) on equilibrium point in order to keep the object at desired position. Several techniques have appeared recently in the literature to control the maglev system.

Hassanzadeh et. al. [7] used GA (Genetic Algorithm) to design controller parameters for unstable Maglev and used xPC target and Simulink to implement proposed algorithm. By Abdel-Hady and Abuelenin [8], indicated a technique based on fuzzy logic to improve the performance of Maglev controlled by PID controller. Ahmad and Javaid [9] proposed linear and non-linear controllers for desired reference trajectory of Maglev. Kumar et. al. [6] presented PID controller to stabilize the system and for trajectory tracking of Maglev, LQR (Linear Quadratic Regulator) approach was used to obtain the parameters of PID controller. Sathiyavathi et. al. [10] proposed Hybrid ILC technique for Maglev. They designed ILC with PID controller for reference tracking of ball. With this proposed controller the closed loop system has 5.58sec settling time which needed to be improved.

Huang et. al. [11] used two electromagnets to enhance the stability of Maglev. Duka et. al. [1] proposed IMC (Internal Model Control) based PID controller for the levitation of ball at desired position. Unni et. al. [5] modeled maglev and proposed LQR, LQG (Linear Quadratic Gaussian) and Fuzzy Controller to control the system. Magaji et. al. [12] proposed Fuzzy Logic based PI and PD Controllers for the Maglev. Hajimani et. al. [13] proposed Neural Adaptive Method for the reference tracking of ball in Maglev. Verma et. al. [14] proposed simple PID controller and FOPID controller design for the levitation of ball in the system.

Sgaverdea et. al. [15] proposed the design and implementation of MPC (Model Predictive Controller) for Maglev. With this proposed control strategy, the closed loop system has more than 10% overshoot which needs to be improved. Hypiuseva et. al. [16] proposed robust PID Controller for unstable Maglev and D-partition technique is used to obtain the PID controller parameters.

Sahoo et. al. [24] proposed fuzzy logic controller for the control of the position of a ferromagnetic ball in Maglev. With this proposed technique, the close loop system has 0.4sec settling time, 28.57% steady state error, 0.135sec rise time and 0% overshoot. ISE of controller output is 139.8. Fuzzy logic controller has removed overshoot but steady state error, rise time and ISE needs to be improved.

Yaseen et. al. [25] presented PID controller, LQR controller and lead compensator to stabilize the Maglev system. With these controllers, settling time and rise time is minimum but peak overshoot with PID controller is 43.6, and 39.3% with lead compensator and 0.505% with LQR. Although LQR controller has minimized the overshoot but failed to remove the overshoots completely.

ILC based FOPID controller for Maglev is presented in this study. Hybrid P-type, PD-type and PID-type ILC are used in cascade with FOPID controller. As Maglev is nonlinear, firstly it is linearized at equilibrium point. ILC cannot be used for unstable system directly because ILC gives an open loop control for a system so if a system is unstable the error will never be minimized, and ultimately desired response can never be achieved. Therefore, FOPID controller is used to stabilize the system. After stabilizing the system, hybrid ILC technique is used to improve the transient response of maglev. Hybrid ILC iteratively minimizes the error. Performance indices like overshoot, steady state error, settling time, ISE and IAE is minimized with proposed technique.

This paper is structured as:

Mathematical modeling of Maglev is discussed in section II. The proposed FOPID and ILC based FOPID controller is presented in Section III. Section IV describes the results and discussion. The concluding remarks are presented in section V.

2. MATHEMATICAL MODELLING OF MAGLEV

Maglev is a complete laboratory system which is used in many real-world applications. The simple illustration of maglev system free body diagram is shown in Fig. 1 [10]. The force F generated by the magnet is increased up to the extent so that it compensates the gravitational force acting on the metallic sphere.

2.1 Nonlinear Mathematical Model

The nonlinear mathematical model of maglev is given by [17]:

$$\dot{x}_1 = x_2 \tag{1}$$

$$\dot{x}_2 = \frac{F_{em}}{m} + g \tag{2}$$

$$\dot{x}_3 = \frac{1}{f_i(x_1)} (k_1 u + c_1 - x_3) \tag{3}$$

$$F_{em} = x_3^2 \frac{F_{emp1}}{F_{emp2}} \exp\left(-\frac{x_1}{F_{emp2}}\right) \tag{4}$$

$$f_i(x_1) = \frac{f_{emp1}}{f_{ip2}} \exp\left(-\frac{x_1}{f_{ip2}}\right) \tag{5}$$

where,

$$x_1 \in [0, 0.016], x_2 = 0, x_3 \in [x_{3MIN}, 2.38], u \in [u_{MIN}, 1]$$

The electromagnetic force (F_{em}) depends on two variables: x_1 and x_3 , where x_1 = Position of the ball from electromagnet, x_2 = ball velocity, and x_3 = Current in magnetic coil.

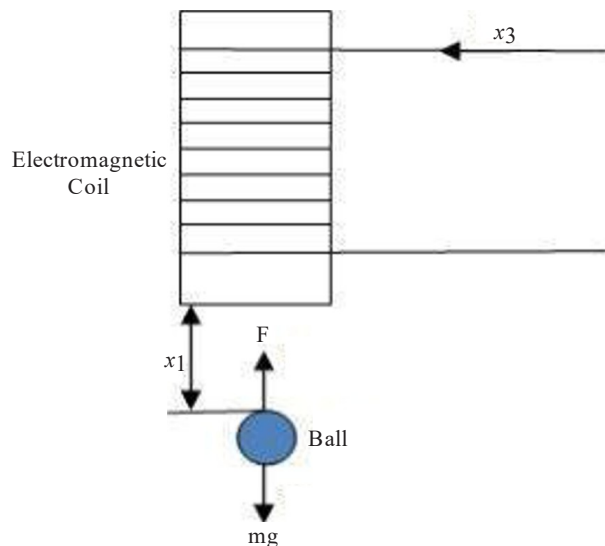


FIG. 1. SIMPLE ILLUSTRATION OF MAGLEV

The parameters of the Maglev used in Equations (1-5) are given in Table 1 [17]:

2.2 Linearized Mathematical Model

Maglev is a nonlinear system because of magnetic field and approximate linear model can be achieved around some equilibrium point. As the system is third order, so it can be approximated by three first order differential equations. The general state space model is [17]:

$$\dot{x} = Ax + Bu \tag{6}$$

$$y = Cx \tag{7}$$

$$A = \begin{bmatrix} 0 & 1 & 0 \\ a_{2,1} & 0 & a_{2,3} \\ a_{3,1} & 0 & a_{3,3} \end{bmatrix} \tag{8}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ b_3 \end{bmatrix} \tag{9}$$

$$C = [1 \ 0 \ 0] \tag{10}$$

$$\text{where, } a_{2,1} = \frac{a_{30}^2 F_{emP1}}{m F_{emP2}^2} \exp\left(-\frac{x_{10}}{F_{emP2}}\right) \tag{11}$$

$$a_{2,3} = \frac{2x_{30} F_{emP1}}{m F_{emP2}} \exp\left(-\frac{x_{10}}{F_{emP2}}\right) \tag{12}$$

$$a_{3,1} = -(k_1 u + c_1 - x_3) \left(-\frac{f_{iP1}}{f_{iP2}^2} \exp\left(-\frac{x_{10}}{f_{iP2}}\right) \right)^2 \tag{13}$$

$$a_{3,3} = -f_i^{-1}(x_{10}) \tag{14}$$

$$b_3 = k_i f_i^{-1}(x_{10}) \tag{15}$$

The next part is the selection of equilibrium point which naturally would be a point at which the velocity of the ball becomes zero. That is, it is stabilized and the two forces (gravitational force of the ball and electromagnetic force) become equal. For linearized model the equilibrium point is selected at about $x_{10} = 0.009m$. For this equilibrium point amount of current flowing through the

TABLE 1. PARAMETERS OF MAGLEV

Parameters	Values
M	0.0571 (kg)
G	9.81(m/s ²)
F _{em}	Function of x ₁ and x ₃ (N)
F _{emP1}	1.7521x10 ⁻² (H)
F _{emP2}	5.8231x10 ⁻³ (m)
f(x ₁)	Function of x ₁ (1/s)
f _{p1}	1.4142x10 ⁻⁴ (m.s)
f _{p2}	4.5626x0 ⁻³ (m)
c _i	0.0243 (A)
k ⁱ	2.5165 (A)
x _{3MIN}	0.03884 (A)
u _{MIN}	0.00498

electromagnet coil is approximately $x_{30} = 0.9345A$. The ball is stabilized at these points and its velocity remains zero [17].

For these equilibrium points, $a_{2,1}$, $a_{2,3}$, $a_{3,1}$, $a_{3,3}$, and $b_{3,3}$ become constant and their values are given as:

$$a_{2,1} = 1.6866e + 03, a_{2,3} = -21.0077, a_{3,1} = 1.6866e + 03,$$

$$a_{3,3} = -21.0077, a_{3,1} = 4.3036e - 04, a_{3,3} = -231.9387 \text{ and } b_{3,3} = 583.6738$$

Updating the above constants in their respective matrices, the system Matrix-A, input Matrix-B and output Matrix-C becomes

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 1.6866e + 03 & 0 & -21.0077 \\ 4.3036e - 04 & 0 & -231.9387 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 \\ 0 \\ 583.6738 \end{bmatrix}$$

$$C = [1 \ 0 \ 0]$$

Using the above state space model the transfer function of the system from voltage (input) to position (output) is given as follows:

$$G_p(s) = \frac{-1.226 \times 10^4}{s^3 + 231.9s^2 - 1687s - 3.912 \times 10^5} \quad (16)$$

3. MAGLEV CONTROL USING HYBRID ILC

FOPID and ILC based FOPID controllers are designed for the stability and reference tracking of maglev with minimum transient errors. FOPID controller is designed for the stabilization of the system then hybrid ILC is used to improve the transient response.

3.1 Fractional Order PID Controller

Podlubny [18] proposed the concept of FOPID (Fractional Order PID) Controller. It consists of fractional order integrator and fractional order differentiator. The general mathematical form of FOPID Controller is given by:

$$G_c(s) = k_p + \frac{k_i}{s^\alpha} + k_d s^\beta \quad (17)$$

Where k_p is proportional gain, k_i is integral gain and k_d is derivative gain. α and β are the fractional powers of integrator and differentiator respectively. Their values lie between 0.1 and 2. When $\alpha = \beta = 1$ then FOPID controller becomes simple PID controller.

FOPID has five unknown parameters. There are many classical and modern techniques to tune these parameters. Dominant pole placement method is used in this research work for FOPID controller design. The FOPID controller parameters are obtained from this technique through optimization of objective function. Nonlinear interior point optimization is used to optimize the objective function in order to find the value of the controller parameters k_p , k_i , k_d , α and β [19].

The design specifications for this system are:

$$\text{Damping Ratio} = \zeta = 0.9$$

$$\text{Setting Time} = t_s = \frac{4}{\zeta \omega_n} \leq 1s$$

According to above specifications of the Maglev the dominant poles are gained from the characteristic equation $(s^2 + 2\zeta\omega_n s + \omega_n^2)$ are:

$$s_{1,2} = -3.996 \pm 1.934i \quad (18)$$

The parameters of FOPID controller can be obtained by the minimization of the objective function:

$$f = |R| + |I| \quad (19)$$

R is the real part of the characteristic equation when we substitute the dominant pole s_1 and I is the imaginary part of the characteristic equation.

Characteristic equation of Maglev with FOPID controller is:

$$1 + G_p(s_1) G_c(s_1) = 0 \quad (20)$$

By putting the value of s_1 from Equation (18) and extracting the real and imaginary parts, we have

$$R = 1 + b_1 K_p = \left(\frac{b_1}{b_2^\alpha} \times \cos(b_3 \alpha) - \frac{b_4}{b_2^\alpha} \times \sin(b_3 \alpha) \right) k_i + \left(0.0316 \times b_2^\beta \times \cos(b_3 \beta) - b_4 \times \sin(b_3 \beta) \right) k_d \quad (21)$$

$$I = -b_4 K_p + \left(\frac{-b_1}{b_2^\alpha} \times \sin(b_3 \alpha) - \frac{b_4}{b_2^\alpha} \times \cos(b_3 \alpha) \right) k_i + \left(b_1 \times b_2^\beta \times \sin(b_3 \beta) - b_4 \times \cos(b_3 \beta) \right) k_d \quad (22)$$

where

$$b_1 = 0.0316, b_2 = 4.394, b_3 = 25.82 \text{ and } b_4 = 2.8437 \times 10^{-7}$$

By substituting Equations (21-22) in Equation (19), we have

$$f(x) = \text{abs} \left(1 + b_1 K_p + \left(\frac{b_1}{b_2^\alpha} \times \cos(b_3 \alpha) - \frac{b_4}{b_2^\alpha} \times \sin(b_3 \alpha) \right) \right) k_i + \left(0.0316 \times b_2^\beta \times \cos(b_3 \beta) - b_4 \times \sin(b_3 \beta) \right) k_d + \text{abs} \left(-b_4 K_p + \left(\frac{-b_1}{b_2^\alpha} \times \sin(b_3 \alpha) - \frac{b_4}{b_2^\alpha} \times \cos(b_3 \alpha) \right) \right) k_i + \left(b_1 \times b_2^\beta \times \sin(b_3 \beta) - b_4 \times \cos(b_3 \beta) \right) k_d \quad (23)$$

This objective function is optimized by nonlinear interior point method in MATLAB subjected to various constraints.

Minimize $f(x)$

Subject to

$$h_i(x) = 0, i = 1, 2, \dots, p$$

$$g_j(x) \leq 0, j = 1, 2, \dots, m$$

$f(x)$ represents nonlinear objective function given in Equation (23). $h_i(x)$ represents equality constraints and $g_j(x)$ represents m inequality constraints.

The closed loop illustration of maglev with FOPID controller is shown in Fig. 2. Here $G(S)$ is transfer function of maglev system and FOPID controller is used to stabilize the system.

Table 2 represents the initial guess, limits of controller parameters and final value of the parameters of FOPID controller which are obtained after minimization of objective function using FMINCON toolbox in MATLAB.

3.2 ITERATIVE LEARNING CONTROLLER

Simple definition of ILC is “A control methodology in which the controller generates the control signal depending upon the previous control signal plus error during the iterations”. ILC works to minimize the error iteratively in such a way that the error of second trial is always less than the error of first trial and so on. ILC is like an intelligent control method which is appropriate for controlled systems in which a given task is repeatedly carried out in a limited interval [20].

ILC is an active control scheme which controls the systems in iteration domain, whereas conventional controllers like PID, LQR or MPC control the system in time domain [21,26].

ILC is used in many applications like chemical batch process, robotics and industrial manipulation [22]. The major problem in a feedback system is that if operator repeats the procedure hundred times then every time system will give the same response and error. ILC works iteratively and uses the information from previous iteration and reduces error at each iteration. The control input of past iteration is saved in memory and it is added with some function on error into prior control signal in order to get an exact tracking. One can use P, D, PD, PI and PID-ILC control laws which are used to update the new control input.

In this paper P-ILC, PD-ILC and PID-ILC is used. D-type ILC is most common and general form of ILC. Derivative of error is applied to generate a new control signal through iteration. The mathematical form of D-type ILC is:

$$u(i, k + 1) = u(i, k) + k\dot{e}(i, k) \tag{24}$$

Here derivative of error is multiplied by some gain.

where,

$$\dot{e}(i, k) = \dot{y}(i) - \dot{y}(i, k) \tag{25}$$

Equation (24) represents the error on which derivative operation is performed. The main drawback of D-type ILC is that it causes noise at the output stage which minimize the accuracy of tracking the desired trajectory.

P-type ILC is much simpler than D-type ILC. In this type of ILC simple error is multiplied by some gain to get the desired response. The mathematical form of P-type is [23]:

$$u(i, k + 1) = u(i, k) + ke(i, k) \tag{26}$$

P-ILC gives satisfactory results. PD-ILC uses both proportional and derivative function on error signal to generate new control signal. The mathematical form is:

$$u(i, k + 1) = u(i, k) + k_p e(i, k) + k_d \dot{e}(i, k) \tag{27}$$

Proportional and derivative gains used for the learning of ILC are found to be efficient in improving the results.

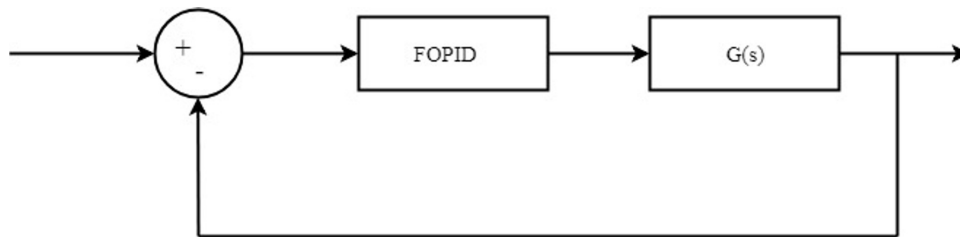


FIG. 2. BLOCK DIAGRAM OF FEEDBACK SYSTEM

TABLE 2. RANGES AND FINAL VALUES OF FOPID CONTROLLER PARAMETERS

Parameters	Initial Guess	Lower Value	Upper Value	Final Value
k_p	-50.95	-51.15	-50.35	-50.45
k_j	-225.55	-225.95	-224.9	-225.8
k_d	-6.9	-7.1	-6.4	-7.086
α	0.80	0.2	0.975	0.900
β	0.60	0.1	0.65	0.5497

PID-ILC uses proportional, derivative and integral function on error signal to generate new control signal. The mathematical form is:

$$u(i, k + 1) = u(i, k) + k_p e(i, k) + k_d \dot{e}(i, k) + k_f \int e(i, k) dt \quad (28)$$

PID-ILC gives best results because integrator removes the steady state error.

There are two basic configurations used in ILC, embedded and cascaded. In embedded, ILC is used by making some changes in the actual loop of the system while in cascaded, without disturbing the existing configuration of the system ILC is integrated independently.

In this research work, cascaded ILC is used. Block diagram of cascaded ILC is shown in Fig. 3. Here ILC is used as an external controller without disturbing the existing control process. ILC uses the desired signal and the error stored from the previous cycle to make a new reference trajectory for the existing control process. In this configuration only few commands for input reference signal have to be re-written and no change in the existing loop has to be done, which is an easy task to carry out practically.

If the error and control signal of previous cycles are used to generate the next control input, then such scheme of learning is called as ILC learning by previous cycle.

Learning through previous cycle does not conceal the disturbance which is present in current cycle. To cover up these disturbances, some kind of feedback mechanism should be used which can be done by making control loop closed in time domain. In this paper, we used FOPID as a feedback controller.

4. SIMULATION RESULTS

FOPID controller is designed for stabilization of the system. It has several advantages over PID controllers due to two additional parameters α and β . It stabilizes the system and helps to track the desired trajectory. The closed loop response of maglev with FOPID controller is shown in Fig. 4.

In Fig. 4, there is 19.3% overshoot in closed loop response with simple FOPID which needs to be improved. Therefore, hybrid ILC is implemented to improve the transient response of the Maglev.

Hybrid ILC is a combination of FOPID and ILC. ILC generates the updated reference signal for existing loop which allows FOPID to easily track the reference signal. Implementation of proposed technique is done by using Simulink and MATLAB. In this research work P, PD and PID control laws are used to design ILC.

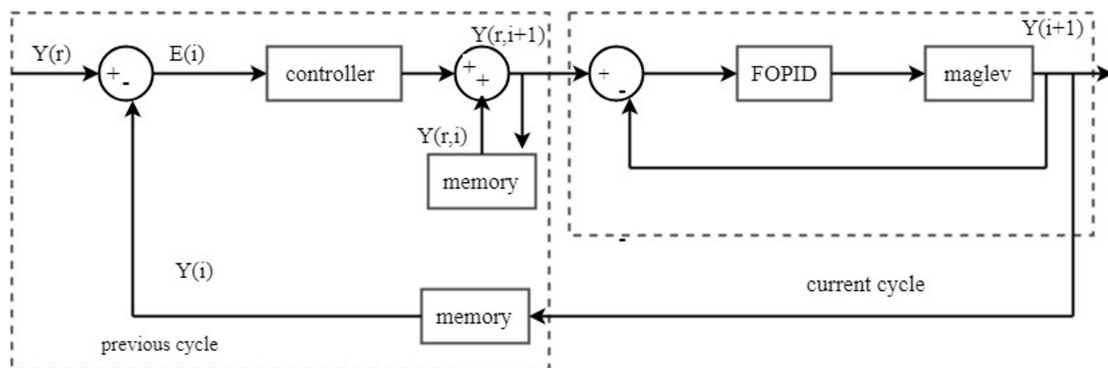


FIG. 3. BLOCK DIAGRAM OF CASCADED ILC

P-ILC and PD-ILC based FOPID controller has removed the overshoot in the system but still there is steady state error. We obtained best results with hybrid PID-ILC, in this case steady state error is zero.

Fig. 5 represents the response of Maglev with hybrid P-ILC at different iterations, Fig. 6 represents the response

of Maglev with hybrid PD-ILC at different iterations and Figs. 7-8 represents the response of Maglev with hybrid PID-ILC at different iterations. Hybrid P-ILC removed overshoot but still there is steady state error after 42 iterations. Steady state error with hybrid PD-ILC is less as compared to hybrid P-ILC. Settling time for the reference is also improved from 1.3-0.6sec.

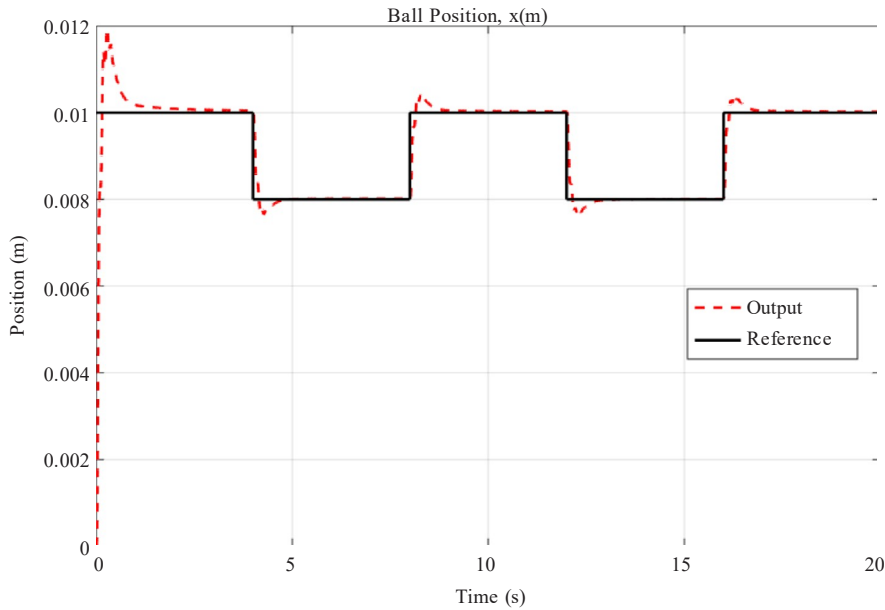


FIG. 4. RESPONSE OF MAGLEV WITH FOPID CONTROLLER

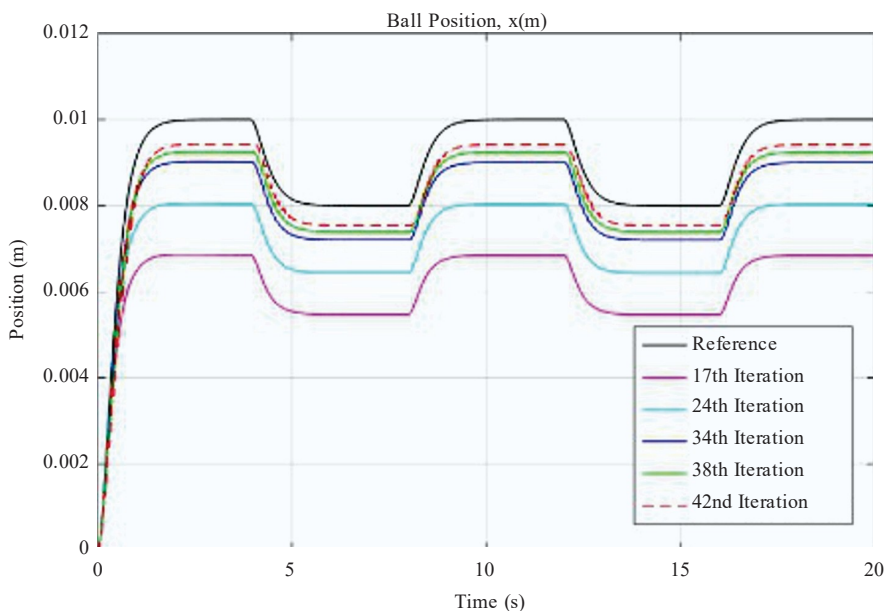


FIG. 5. RESPONSE OF MAGLEV WITH HYBRID P-ILC AT DIFFERENT ITERATIONS

We got best results with hybrid PID-ILC. Steady state error with hybrid PID-ILC is zero as integrator eliminates the steady state error. At first 10 iterations there is overshoot and steady state error but at 20th iteration it perfectly tracks the reference. Fig. 8 represents the

response of Maglev with hybrid PID-ILC at final iteration. It has been analyzed that the performance of hybrid PID-ILC controller has dominated over the hybrid P-ILC, hybrid PD-ILC and simple FOPID controller.

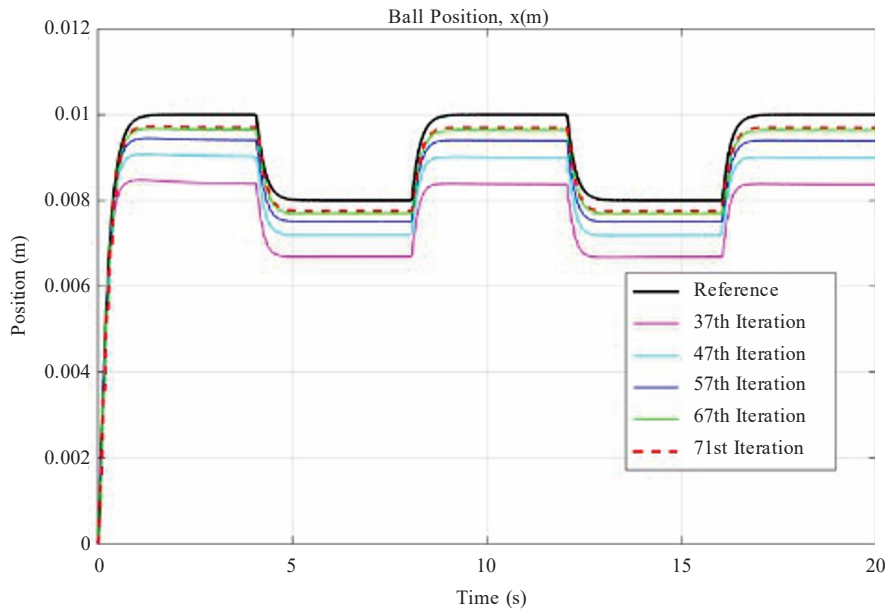


FIG. 6. RESPONSE OF MAGLEV WITH HYBRID PD-ILC AT DIFFERENT ITERATIONS

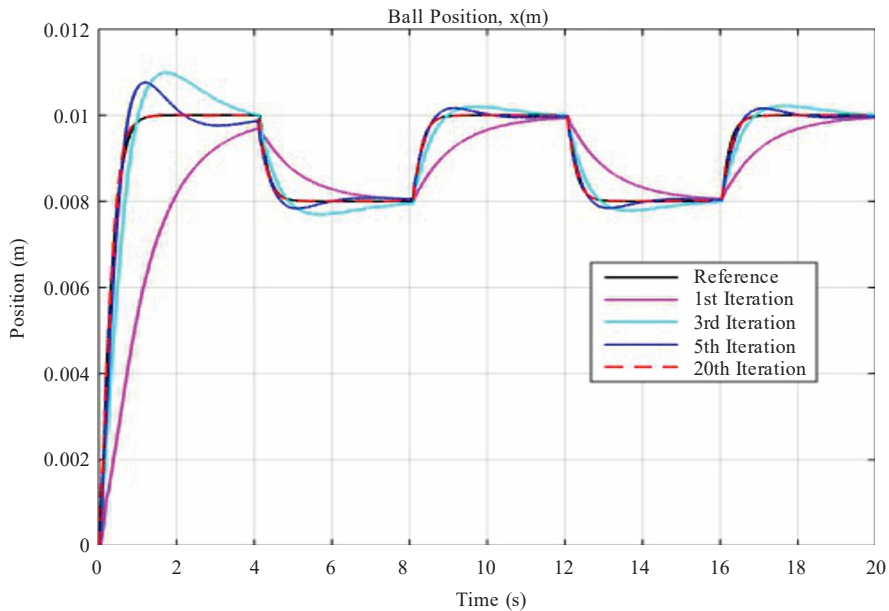


FIG. 7. RESPONSE OF MAGLEV WITH HYBRID PID-ILC AT DIFFERENT ITERATIONS

Figs. 9-11 show the change of maximum absolute value of error per trial of hybrid P-ILC, PD-ILC and PID-ILC. The maximum absolute value of error obtained by hybrid P-ILC is 0.0006 after 42 iterations, 0.0003 after 71 iterations from hybrid PD-ILC and 0.0002 after 20 iterations from

hybrid PID-ILC. Figs 12-15 represent the control effort of different controllers. Control effort is 0.3V in case of hybrid P-ILC and 0.4V in case of FOPID controller, hybrid PD-ILC and hybrid PID-ILC. Fig. 16 represents the response of maglev system with all controllers.

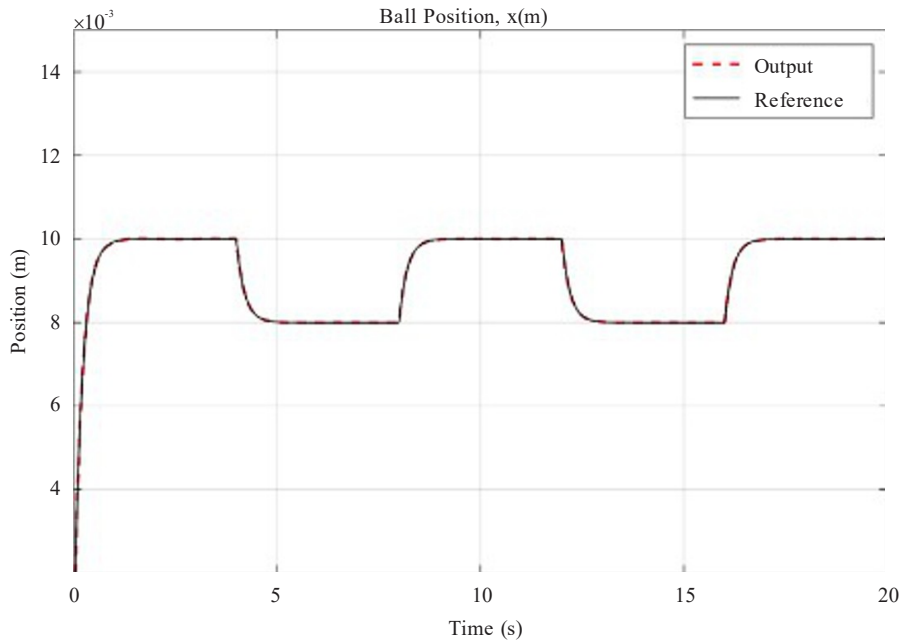


FIG. 8. RESPONSE OF MAGLEV WITH HYBRID PID-ILC AT FINAL ITERATION

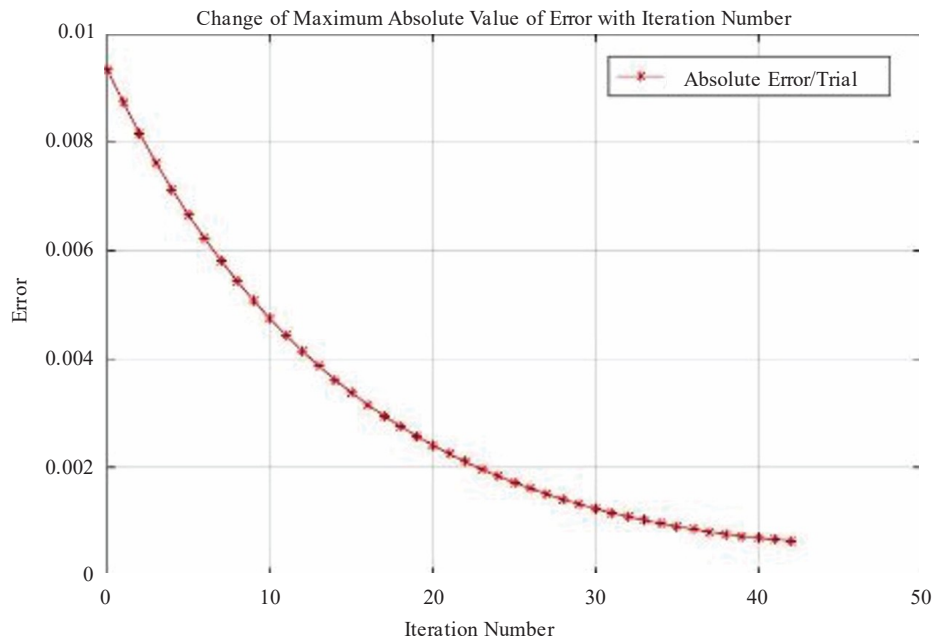


FIG. 9. CONVERGENCE PER TRIAL OF HYBRID P-ILC

Table 3 shows the performance indices of Maglev with both (FOPID and hybrid ILC) controllers. ISE and IAE is minimum in case of hybrid PID-ILC. ISE is 0.002 in case of FOPID controller and 0.000019 in case of hybrid PID-ILC.

IAE is 0.13 in case of FOPID controller and 0.0436 in case of hybrid PID-ILC. Table 4 represents that ISE is minimized 99.1% and IAE is minimized 66% in hybrid PID-ILC as compared to simple FOPID controller.

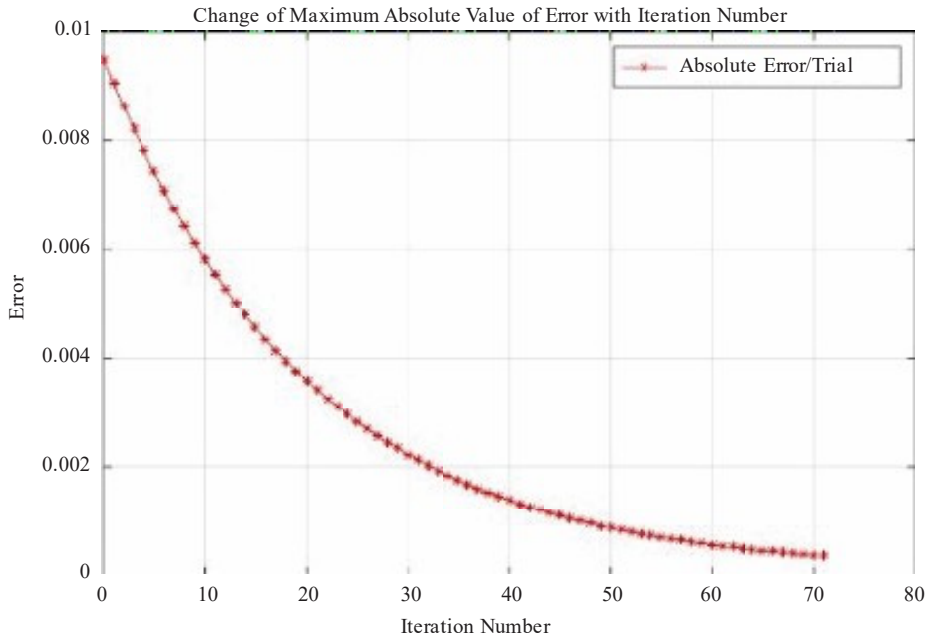


FIG. 10. CONVERGENCE PER TRIAL OF HYBRID PD-ILC

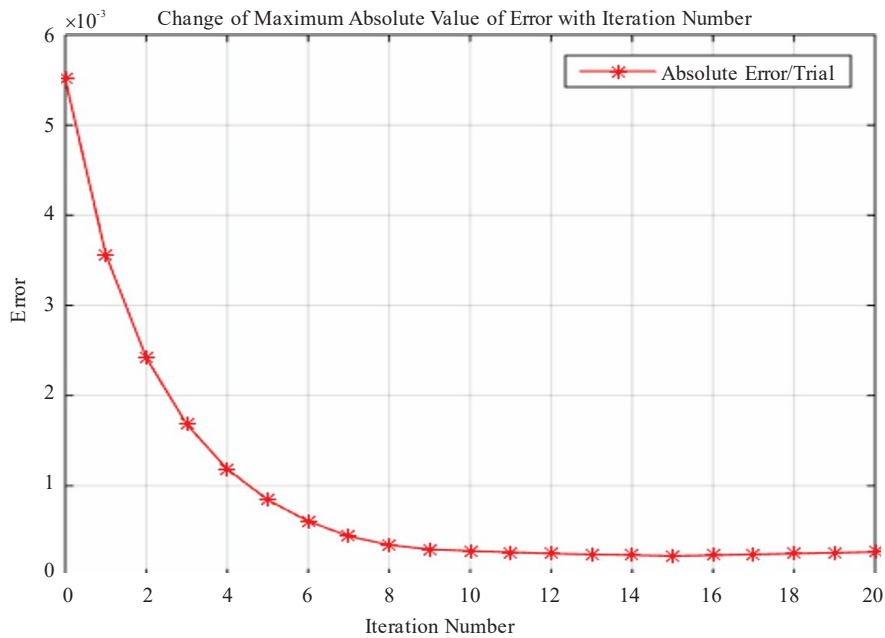


FIG. 11. CONVERGENCE PER TRIAL OF HYBRID PID-ILC

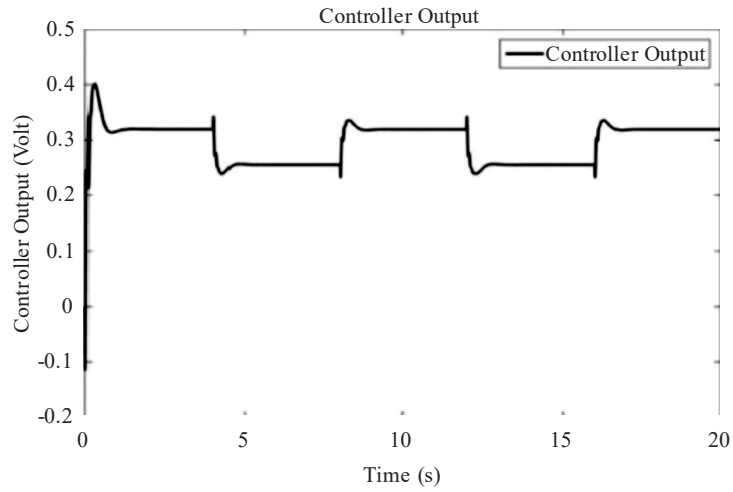


FIG. 12. FOPID CONTROLLER OUTPUT

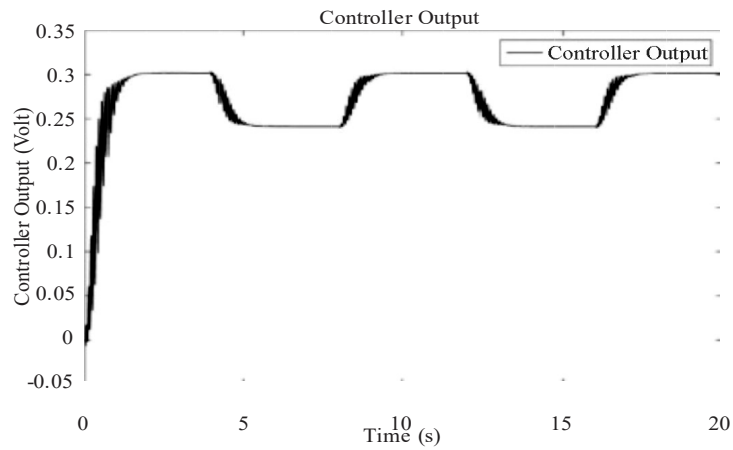


FIG. 13. HYBRID P-ILC CONTROLLER OUTPUT

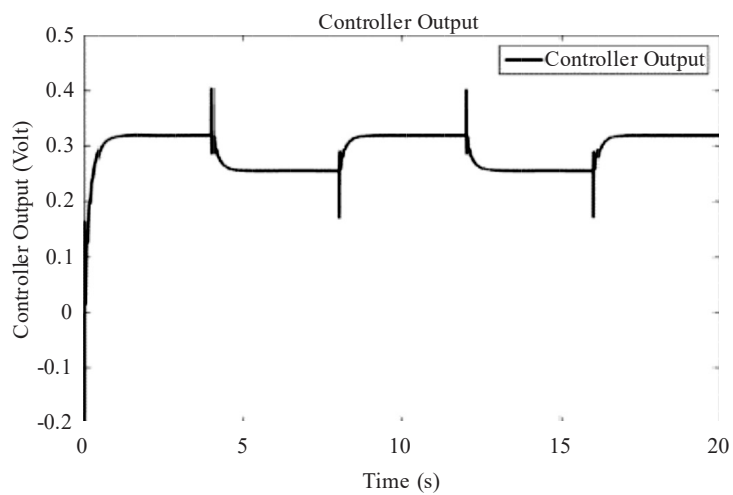


FIG. 14. HYBRID PD-ILC CONTROLLER OUTPUT

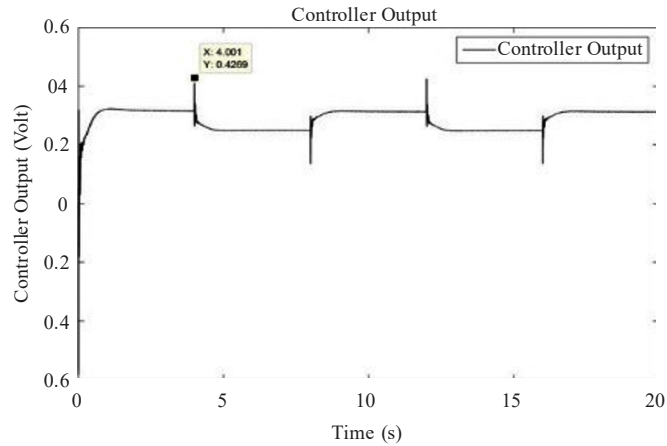


FIG. 15. HYBRID PID-ILC CONTROLLER OUTPUT

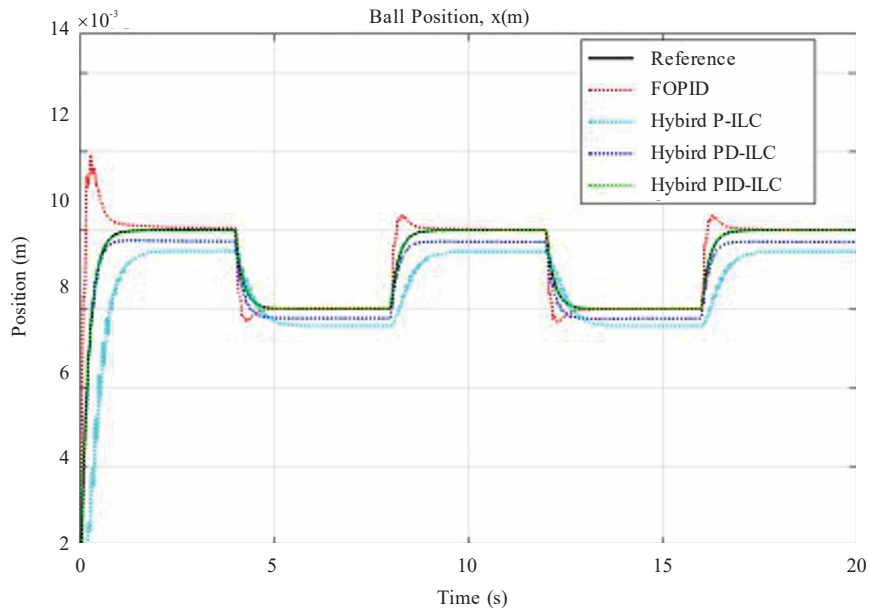


FIG. 16. RESPONSE OF MAGLEV WITH ALL CONTROLLERS

TABLE 3. TIME DOMAIN PERFORMANCE PARAMETERS OF MAGLEV WITH FOPID AND HYBRID ILC

Controller	Overshoot (%)	Rise Time (sec)	Settling Time (sec)	Peak Time (sec)	Steady State Error	ISE	IAE
FOPID	19.3	0.11	0.9019	0.277	0.00001	0.0022	0.13
Hybrid P-ILC	0	0	1.3	0	0.0005	0.0016	3.0549
Hybrid PD-ILC	0	0	0.6	0	0.0002	0.000455	1.6247
Hybrid PID-ILC	0	0	0.6	0	0	0.000019	0.0436

TABLE 4. PERCENTAGE IMPROVEMENT

Performance Indices	FOPID	Hybrid PID-ILC	Improvement (%)
ISE	0.0022	0.000019	99.1
IAE	0.13	0.0436	66.0

5. CONCLUSION

In this paper FOPID controller for Maglev is designed. The FOPID controller parameters are obtained through non-linear interior point optimization. A hybrid arrangement of ILC is used in this research work. FOPID is used in feedback, while ILC is used as a feed forward controller. A combination of feedback and feed forward controller allows the system to completely track the reference signal. FOPID stabilize the system while ILC improves the transient response by learning through trials. The effectiveness of proposed technique is analyzed through performance indices like overshoot, peak time, settling time, steady state error, rise time, ISE and IAE. Results show that proposed hybrid PID-ILC stabilizes the ball in the desired position.

6. NOMENCLATURE

M	Mass of the ball
G	Gravity constant
x_1	Position
x_2	Velocity
x_3	Current
$f_1(x_1)$	Function of x_1
k_p	Proportional gain
k_d	Derivative gain
k_i	Integral gain
ω_n	Natural frequency
c_i	Current gain
F_{em}	Electromagnetic force
F_{emP1}	Parameter of electromagnetic force (H)
F_{emP2}	Parameter of electromagnetic force (m)
f_{ip1}	Actuator parameter
f_{ip2}	Actuator parameter
A	System Matrix
B	Input Matrix
C	Output Matrix
Ξ	Damping ratio
t_s	Settling time
exp	Exponential

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