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Nature Inspired Computation Based Fractional Order I-TD and TID Controllers for Magnetic Levitation System

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Abstract- Magnetic Levitation System is an intricate open loop unstable system having various uncertainties. In this paper, fractional order controllers including Tilt Integral Derivative and Integral-Tilt Derivative have been utilized for the stability control of the system. The optimal values of the proposed controllers are tuned using Teaching Learning Based Optimization and Cuckoo Search Algorithms. Further, the transient performance of the system with the proposed controllers have been evaluated using four different objective functions including integral of square error, integral of absolute error, integral of time multiplied by absolute error and integral of time multiplied by squared error. A comprehensive comparative performance analysis between proposed controllers and tuning methodologies has been carried out. Simulations have been done via MATLAB/Simulink tool. Simulation results reveal that proposed control strategies yield a stable response of the system with satisfactory transient and steady state response in terms of settling time, rise time, and steady-state error. Furthermore, it is apparent from the results that TID controller overall yields better settling time and steady-state error as compared to I-TD, while I-TD yields relatively small overshoot.

Keywords- Fractional Order controllers, Magnetic Levitation System, Tilt Integral Derivative (TID), Integral-Tilt Derivative (I-TD), Nature Inspired Computational (NIC),Teaching Learning Based Optimization (TLBO), Cuckoo Search Algorithm (CSA).

I. INTRODUCTION

Magnetism is a vital part of our universe. It makes earth to spin around its own axis thus producing gravity. One of the exquisite applications of magnetism or electromagnetic harvester is Magnetic Levitation System (MLS) [1]. MLS is a benchmark for the study and analysis of magnetic levitation technology. Magnetism properties have been incorporated in medical, aerospace, energy and petroleum industries and some of these applications includes mass spectrometry, Maglev trains, electrodynamics suspension, nuclear reactor, wind turbines, cathode ray tubes, Magnetic Resonance Imaging (MRI) [2]. Mass spectrometry is a significant instrument that is used to measure the mass to charge ratio of the isotopes and identify them. Another application of magnetism is Cathode Ray Tubes or simply known as electron gun and they are widely used in televisions, x-ray machine and others. They accelerate the electrons and steer them to achieve the desired result. Aerospace industry used this phenomenon to balance the rocket and space shuttles. Magnetic Resonance Imaging (MRI) is a major outbreak in the medical industry that gives three-dimensional images of the body that can be utilized without the hazards of x-rays. Friction less property of MLS establishes its importance in the field of transportation and aviation.

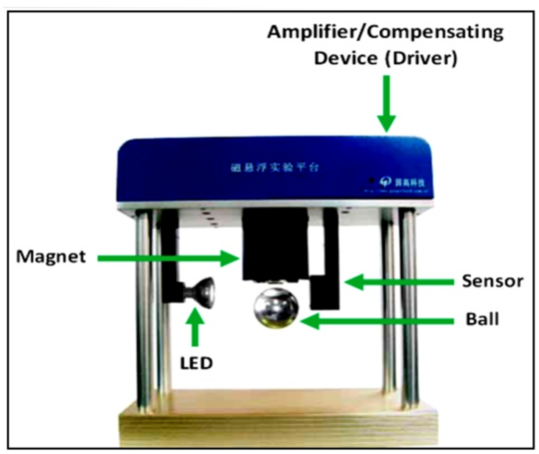

Figure 1: Magnetic Levitation System

MLS is composed of position sensor, solenoid, controller, steel ball, amplifier/compensation device (driver) as shown in Figure 1. Magnetic levitation system applies the magnetic field to levitate a magnetic object in close vicinity. In MLS, an electromagnetic force is produced when certain amount of current passes through the solenoid. The electromagnetic force equals to the weight of the steel ball (control object), by controlling the current, that passes through the solenoid such that the steel ball can levitate in the air, while it is in equilibrium state. MLS is intrinsically non-linear and unstable system that always requires a robust feed-back controller to adjust electromagnet in the system to bring the levitated magnetic object at a desired position [3].Typical controllers that can be employed are PID, root locus and frequency controller, state space controller, fuzzy based controller, neural network and adaptive controllers. Simple PID controller may not be suitable to deal with the uncertainties that MLS possesses. In past several heuristic and classical tuning strategies have been adopted for the optimum control of MLS. In [4], authors have designed a TLBO algorithm based PID controller for the performance enhancement of MLS.IMC based PID controller for MLS has also been implemented. Heuristic computation based algorithms have been widely used in recent past for the tuning of different controllers. GA based PID controller has been successfully implemented to control the MLS [5]. These controllers have shown promising results but MLS performance can be further enhanced by adopting fractional order controllers.

These fractional order controllers are very adaptive for open-loop unstable systems such as MLS. A simplified fractional order controller has also been proposed for MLS there in [6]. Moreover, optimal pole-zero approximation based digital fractional order PID controller is also implemented for the position control of MLS [7].Genetic Algorithm (GA) based I-TD and TID controllers have been recommended for the said purpose [8]. A state feedback controller has also been successfully used for the control of MLS. Several other methods have also been employed to achieve the efficient response of MLS [9]. Further, Fuzzy back-stepping, LQR state observer and self-tuned full-state feedback controllers have also been implemented for optimum control of Magnetic Levitation System (MLS)[10-14]. In [15] Ahmed and et al have adopted Neural Network and Genetic Algorithm methodology to obtain PID controller parameters. Neural Network approach achieves better transients than traditional PID controller while GA based system provides better results in every respect as compared to rest of the methods. In another research work [16] Fares and et al investigates the performance of Fuzzy based Proportional Derivative controller for MLS. Fuzzy based PD controller successfully stabilizes the system while providing optimum transients. Sain and et al [17] have demonstrated novel set point PID controller tuned with TLBO algorithm for MLS. A comprehensive comparison is presented with conventional 1-DOF (Degree of Freedom) 2-DOF PID controllers. In terms of system's transient response, novel set point PID controller outperforms the others in achieving lower overshoot and settling time.

In this research work, fractional order TID and I-TD controllers have been explored to optimize the transients such as overshoot, rise time, settling time and steady state error of the MLS system. Both TID and I-TD controllers have been tuned with NIC algorithms. Furthermore, a comprehensive comparison of the transient response of NIC basedTID and I-TD controllers is presented. Our main contributions in this paper are:

a. Design of I-TD and TID controllers for the Magnetic Levitation System.
b. Optimization of I-TD and TID controllers using NIC algorithms including Cuckoo Search Algorithms (CSA) and Teaching Learning Based Optimization (TLBO).
c. The transient and steady state performance evaluation of I-TD and TID controllers using four different performance indices IAE, ITAE, ISE and ITSE. These performance indices are derived using system's error.

The rest of the paper is compiled as follows:

In section 2, mathematical modelling of MLS is presented. In section 3, problem formulation and controller design is described in which two fractional order (FO) controllers are derived whereas section 4caters the description of NIC algorithms. Four different performance indices, which are utilized in this research work, are given in section 5. Finally, results and discussions provided in section 6.

II. Mathematical Modelling of Magnetic Levitation System (MLS)

MLS is a didactical system, which is categorized by non-linearity, uncertainty and open-loop instability [18, 19]. It is an electromechanical coupling system in which a metal ball levitates against gravity to a desired position with the help of electromagnets. The electromagnet strength depends upon the number of turns of the coil. Figure 2 shows the schematic diagram

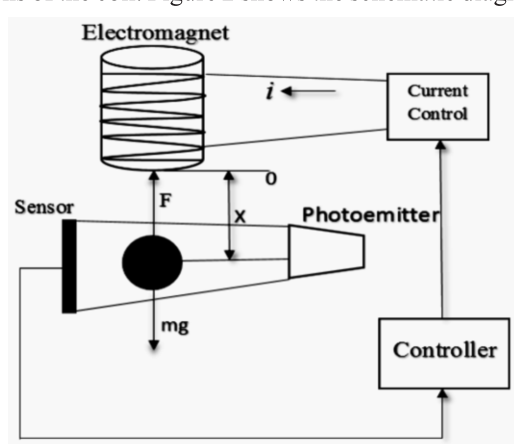

Figure 2: Schematic Diagram of MLS

of MLS, GML 1001 model supplied by Googol-Tech that is used in this work. As noticed, the electromagnetic force 'F' is generated when controller sends the signal to the current control circuitry. The current 'i' will in turn levitates the ball against the force of gravity 'mg'.

The distance 'x' from electromagnet to steel ball is measured by photo-emitter and sensors. The dynamic equation of the system can be described as:

$$m\frac{d^2x(t)}{dt^2}=F(i,x)+mg \quad (1)$$

where,

"x" is the distance from the ball to electromagnet

"m" is the steel ball mass.

"F" is the electromagnetic force.

"g" is the gravitational acceleration.

The reluctance $R(x)$ in air gap can be defined as:

$$R(x)=\frac{l}{\mu A_o}+\frac{2x}{\mu_o A} \quad (2)$$

Where,

"l" is the iron core's magnetic induction length.

"μ" is the relative magnetic permeability of iron core.

"μ_o" is the relative magnetic permeability of air ($\mu_o = 4\pi x 10^{-7} H/m$).

"A_o" is the cross sectional area of iron core.

"A" is the cross sectional area of air gap.

Due to iron magnetic material, the reluctance is of small magnitude. Thus, the first part of (2) can be neglected.

$$R(x)=\frac{2x}{\mu_o A} \quad (3)$$

We can write using Kirchhoff's law,

$$Ni=\varphi(i,x)R(x) \quad (4)$$

$$\emptyset(i,x)=\frac{Ni}{R(x)} \quad (5)$$

Substituting for R(x) from (3) we get,

$$\emptyset(i,x)=\mu_o\frac{i}{2x} \quad (6)$$

Let us assume that electromagnet is not working in saturation state (magnetism), and suppose that magnetic flux is same in each winding. Therefore, the winding magnetic flux linkage number can be written as:

$$\varphi(i,x)=N\emptyset(i,x)=\mu_o AN^2\frac{i}{2x} \quad (7)$$

The magnetic flux Φ and current (I) are related to each other as:

$$N\emptyset = LI \quad (8)$$

The instantaneous inductance can be defined as:

$$L(i,x)=\frac{\varphi(i,x)}{i}=\frac{\mu_o AN^2}{2x} \quad (9)$$

The power of magnetic field $W_m(i,x)$ can be written as:

$$W_m(i,x)=\frac{1}{2}L(i,x).i^2 \quad (10)$$

The magnetic force (F) can be defined as:

$$F(i,x)=\frac{\partial W_m(i,x)}{\partial x}=\frac{\partial\left(\frac{N^2\, i^2\, A\, K_f\, \mu_o}{4x}\right)}{\partial x}$$

$$F(i,x)=\frac{i^2N^2 A\, K_f\, \mu_o}{4x^2} \quad (11)$$

where,

"K_f" is the magnetism inductance of the ball,.

"N" is the electromagnetic winding turns.

"i" is the instantaneous current in the coil.

Considering N, A, K_f and μ_o are constants, magnetic force can be written as:

$$F(i,x)=K\frac{i^2}{x^2} \quad (12)$$

where,

$$K=\frac{N^2A\, K_f\, \mu_o}{4}$$

As magnetic force "$F(i,x)$" is negative proportional to the air gap "x", it makes the system unstable. The relationship between coil voltage and current is described as U(t):

$$U(t)=R.i(t)+L_1\frac{di}{dt} \quad (13)$$

where,

"L_1" the static inductance when ball is in the magnetic field.

"R" is the winding resistance of electromagnet.

When the ball is in equilibrium magnetic force can be expressed as:

$$mg+F(i_o,x_o)=0 \quad (14)$$

After linearizing the system around equilibrium point (i_o, x_o), equation of the whole system can be written as:

$$m\frac{d^2x}{dt^2}=K_i(i-i_o)+K_x(x-x_o) \quad (15)$$

where,

"K_i" is the stiffness co-efficient of the magnetic force and

"K_x" is the stiffness co-efficient of the magnetic force to air gap

By taking Laplace transform and substituting the physical values of different parameterstabulated in Table 1, the equivalent transfer function($G_P(s)$) can be derived as:

$$G_p(s)=\frac{Y(s)}{U_{in}(s)}=\frac{77.8421}{0.0311s^2-30.5250} \quad (16)$$

Table:1 Parameters of MLS

Parameter	Value	Parameter	Value
Enameled wire diameter	Φ 0.8mm	Iron core diameter	Φ 22mm
N	2450 circles	K_f	0.25
x_o	20mm	m	22g
R	13.8Ω	r	12.5mm
K	2.3142e-4 Nm^2/A^2	i_o	0.6105 A

III. Problem Formulation and Proposed Control Methodology

The transfer function of the system under study given by (16) is evidently open-loop unstable. Further, Figure 3 shows the open- loop step response of the system which clearly shows that the output response is exponentially growing and unstable.

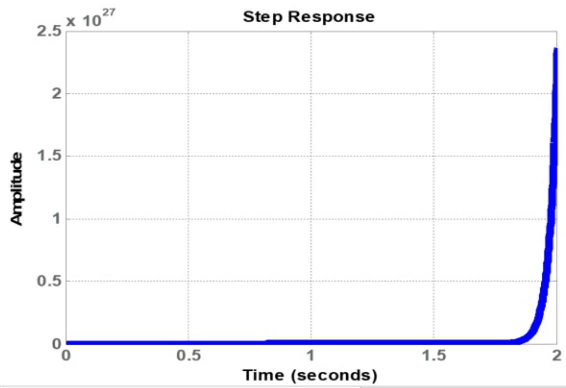

Figure 3: Open-Loop Response of MLS

Since MLS is an open-loop unstable system, therefore it requires controller to stabilize the system with satisfactory transient response. Fractional order controllers are type of non-conventional controllers developed in the last few decades [20]. It has been found that fractional order controllers are more robust and adequate models as compared to conventional controllers. TID and I-TD are two such fractional order controllers employed in this research paper for the stability control of magnetic levitation system. Furthermore, nature inspired metaheuristic computational techniques have been utilized for the optimal parameter tuning of these controllers to achieve the stable and satisfactory transient response.

3.1. TID CONTROLLER

TID controller is analogous to PID controller, the difference lies in the proportional term of the compensator, which is replaced with a tilted component 'K_t' having frequency domain representation as $s^{-1/n}$.This fractional term, which is shaped in accordance with gain/frequency of a compensation unit makes TID more robust and improved controller as compared to simple PID controller. 'n' is a non-zero number preferably between 2 and 3 for the Tilt compensator. In addition to tilted compensator, other parameters are derivative 'K_d' and integral 'K_i' gains that can be optimized through heuristic or other conventional tuning methods [21]. TID controller's transfer function can be written as:

$$G_{TID}(s) = \frac{s^2K_d + s^{1/2}K_t + K_i}{s} \quad (17)$$

3.2. I-TD CONTROLLER

I-TD is a modified form of TID controller, in which the integral compensator acts on the process in the forward path whereas derivative and tilt compensators act in the feedback path. Like TID, I-TD is also a robust controller having capacity of eliminating different disturbance from the system. I-TD controller's transfer function including process can be written as:

$$G_{I-TD}(s) = \frac{AK_i}{s^3B + s^2AK_d - sC + s^{1/2}AK_t + AK_i} \quad (18)$$

where A, B and C are system constants. K_d, K_i and K_t are Derivative, Integral and Tilt gains respectively.

IV. Tuning of Controllers using Metaheuristic Techniques

Many classical tuning approaches have been utilized to optimize classical and modern controllers but it has been recognized from extensive research work that heuristic techniques are optimal soft computing techniques to achieve desired optimum response of a system. These soft computing tuning techniques are based upon mimicking nature. Two such heuristic computational techniques including Cuckoo Search Algorithms (CSA) and Teaching Learning Based Optimization (TLBO) have been opted in this research to obtain the optimum parameters of proposed TID and I-TD controllers based on four different error criterion [22]. The whole control process is demonstrated in Figure 4.

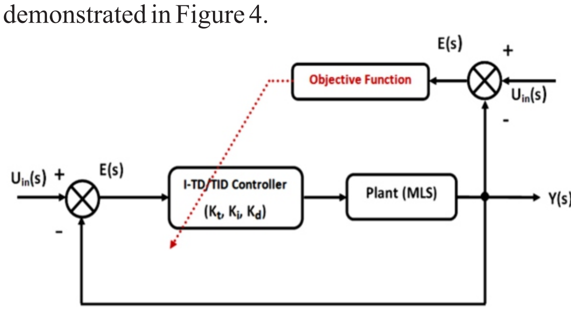

Figure 4: Block Diagram of whole control process

4.1. TEACHING LEARNING BASED OPTIMIZATION ALGORITHM

Teaching Learning Based Optimization is an efficient NIC algorithm that is inspired by the influence of a teacher on its students in a class. It consists of two stages. The first stage i.e., Teacher Phase, in which a teacher directly gives awareness to his/her students. The second stage i.e., Learner Phase, implicates the fact that students may be trained with the help of their fellow students. In general, the knowledge gained by students depends upon the interactions amongst them through peer learning. Infeasible solutions are rejected and replaced with better individuals [23]. In past, TLBO has been successfully used for different

optimization problems [24-27]. Basic Pseudo code of TLBO algorithm is summarized as below:
Step 1: [Initialization]
Initialize the optimization parameters (K_d , K_i , K_t),
- Population size (number of learners): 10
- Number of iterations: 25
- Number of design parameters (K_d , K_i , K_t)
- Limits of design variables (Upper bound = 30, Lower Bound = 0.1)

Step 2: [Initialize population]
Generate random population according to the population size and the number of designed parameters.
Step 3: [Fitness Evaluation]
Evaluate fitness of each population using Eq. 19 to 22 and placed it in a matrix named Cost_Function.
Step 4: [Sorting]
Sort the population according to their fitness value in ascending order to get the best possible solution or get Best_Solution= min (Cost_Function(x)).
Step 5: [Teacher Phase]
Compare the fitness with the best solution (Teacher):

```
% Select Teacher
    Teacher = pop(1);
for i=2:nPop
    if pop(i).Cost<Teacher.Cost
    Teacher = pop(I);
end
```

Step 6: [Student Phase]
Modify solution by simulating the concept: the learning of the students through their mutual interaction
Step 6: [Repeat]
Repeat step 3 until stopping criteria i.e., maximum number of iterations is satisfied.
Step 7: [Stop]

4.2. CUCKOO SEARCH ALGORITHM

Cuckoo Search Algorithm is a swarm intelligence based heuristic computational technique proposed by Yang and et al in 2009[5]. CSA uses less parameters and it has fast convergence. CSA provides optimal solution using principle of cuckoo's brood parasitism. Cuckoo produces one egg at a time and then selects a nest stochastically to hatch it. Among the selected nests, best nest will be reserved for next generation. CSA effectively implements exploration and exploitation. CSA have also been successfully utilized for different engineering optimization problems in recent past [28-32]. Basic Pseudo code of Cuckoo Search via Lévy flightalgorithm is summarized as below:

Begin
Data initialization: Initiate the population of nest i.e., n= (K_d , K_i , K_t), for i=1 to 25 iterations.
While
- Evaluate the fitness of each nest using Eq. 19 to 22 and placed it in a matrix named F.
- Sort the fitness matrix in ascending order or get fmin = min (F(x)).
- Initiate host nest locations and placed them in H matrix.
- Replace the worst host nest xworst on the basis of probability function with a newly generated host nest.
- Run the iterations until you find the best possible solution or host nest.

Stop

V. PERFORMANCE INDICES

Real time control system optimization requires the minimization of an objective function based on some performance index. I-TD and TID controller parameters have been optimized based on different performance indices such as integral of time multiplied by absolute value of error (ITAE), integral of time multiplied by squared error (ITSE), integral of squared error (ISE) and integral of absolute value of error (IAE). The objective is to derive the cost function for each controller and apply a soft computing algorithm for the optimum tuning of the controller. This process will minimize the error in order to acquire best transient and steady state behaviour of the system by controlling the systems dynamics. By minimizing the error, uncertainties in the system can be removed. Performance of a system is determined through a performance index. Performance index is defined as a quantitative measure to observe the system performance of the designated controllers. Using this process required optimized parameters of the controllers can be obtained. These performance indices are defined as:

➢ Integral of time multiplied square error index:

$$ITSE = \int_{t1}^{tf} t \, . \, e(t)^2 \, dt \qquad (19)$$

This index provides similar results as ISE but it also puts weight on the error to be minimized.

➢ Integral of time multiplied absolute error index:

$$ITAE = \int_{t1}^{tf} t \, . \, |e(t)| \, dt \qquad (20)$$

It provides similar results as IAE with the only difference lies in putting more weight on e(t) for larger values of t and less weight on e(t) for smaller value of t.

➢ Integral square error index:

$$ISE = \int_{t1}^{tf} e(t)^2 \, dt \qquad (21)$$

This index minimizes the larger error values very swiftly as compared to other indices. It also proves to be very efficient for set point tracking.

➢ Integral absolute error index:

$$IAE = \int_{t1}^{tf} |e(t)| \, dt \qquad (22)$$

It is appropriate for acquiring optimum step responses, as this index provides optimum transient parameters.

Evaluating the above equations in the cost function of the NIC algorithms, we can achieve minimal error.

VI. Simulation Results and Discussions

In this section, the simulation results via MATLAB/Simulink tool have been are presented to illustrate the effectiveness of the proposed controllers. The unit step input is taken as reference position of the steel ball throughout all simulations. The open-loop response of Figure 3 revealed that MLS is open-loop unstable, therefore feedback controllers including TLBO based TID (TLBO-TID), TLBO based I-TD (TLBO-I-TD), CSA based TID (CSA-TID) and CSA based I-TD (CSA-I-TD) have been implemented to achieve a stable and satisfactory step response. The TLBO and CSA algorithms were executed with the parameter settings as prescribed in algorithm 1 and algorithm 2. Bothe algorithms were run for several trials until we achieved the optimal response of the system. Table 2 shows the optimal values of the controller parameters acquired by TLBO corresponding to the minimum cost function.

Table 2: Optimal values of controller parameters of I-TD and TID controller with TLBO

Performance Index	Controller	K_t	K_i	K_d
IAE	TID	28.91	28.97	2.69
	I-TD	6.41	30	0.5
ITSE	TID	14.82	22.74	0.17
	I-TD	5.43	25.61	0.5
ITAE	TID	16.38	30	1.38
	I-TD	5.77	29.91	0.5
ISE	TID	30	15.56	23.07
	I-TD	4.68	25.72	0.14

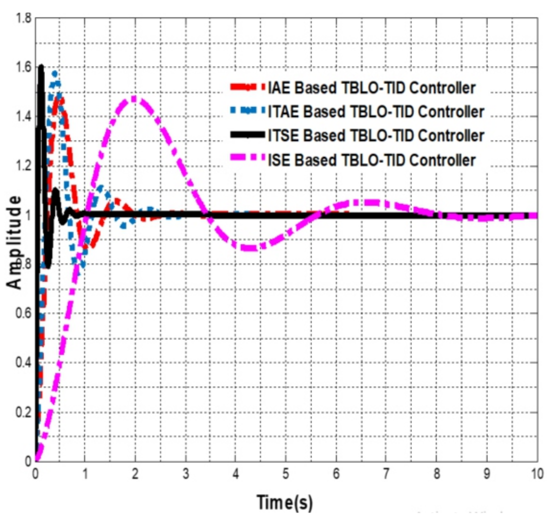

Figure 5: Step Response of TLBO-TID controller with different performance indices

Figure 5 shows the step response of the system with TLBO-TID controller. From Figure 5, it is evident that TLBO-TID controller successfully achieves a stable response with satisfactory transient and steady state performance.
The response of the system with TLBO-I-TD controller is also depicted in Figure 6, which also shows that the proposed control yields a stable response.

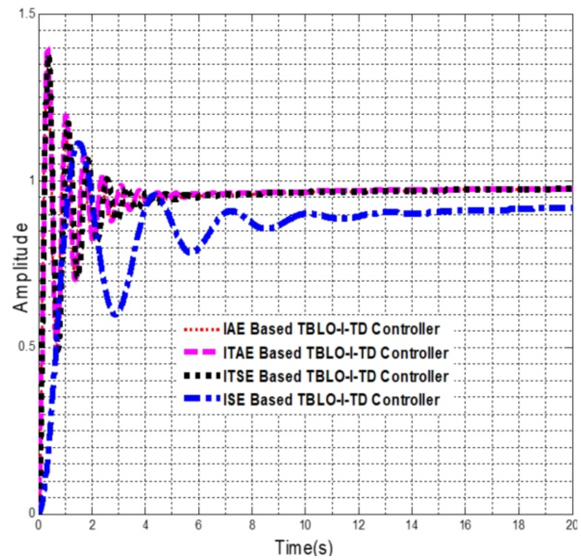

Figure 6: Step Response of TLBO-I-TD controller with different performance indices

In order to compare the transient and steady state performance of TLBO-TID and TLBO-I-TD controllers a comparison between rise time (t_r), settling time (t_s), steady-state error(e_{ss}), and % overshoot (%OS) is presented is Table 3.
It is obvious from the results that that both controllers provide a stable response. From the results of Table 3, it is cleared that TLBO-TID controller with each performance index completely eliminates the steady state error with minimum rise and settling times but gives more % overshoot as compared to TLBO-I-TD controller.
On the other hand, TLBO-I-TD controller undergoes minor steady state error with more settling time but less % overshoot as compared to TLBO-TID controller. Particularly, TLBO-I-TD controller with ISE index completely removes the % overshoot that is too reliable for system's dynamic behaviour.
Next, the performance of TID and I-TD controllers with CSA tuning is evaluated. The algorithm was run for several runs for optimal response of the system.

Table 4 shows the optimal values of controller obtained by CSA based on various cost functions given by (19)-(22).

Table 3: Performance comparison of TLBO based TID and I-TD controllers

Performance Index	Controller	Rise Time (t_r) (sec)	Steady State error (e_{ss})	Settling Time (t_r) (sec)	% Overshoot (% OS)
IAE	TID	0.18	0	1.67	32.61
	I-TD	0.15	2%	4.85	25.59
ITSE	TID	0.043	0	0.47	36.98
	I-TD	0.16	2%	5.28	27.38
ITAE	TID	0.149	0	1.51	36.51
	I-TD	0.15	2%	4.87	28.57
ISE	TID	1.014	0	5.2	32.07
	I-TD	0.99	8%	40	9.23

Table 4: Optimal Values of controller parameters of I-TD and TID controller with CSA

Performance Index	Controller	K_t	K_i	K_d
IAE	TID	30	23.09	4.43
	I-TD	5.91	18.97	1.69
ITSE	TID	30	30	1.89
	I-TD	2.95	7.73	0.74
ITAE	TID	21.64	30	0.95
	I-TD	8.53	30	0.69
ISE	TID	19.63	21.29	30
	I-TD	7.1	15.87	0.93

Figure 7 and Figure 8 show the step response of the system with CSA-TID and CSA-I-TD controllers respectively.

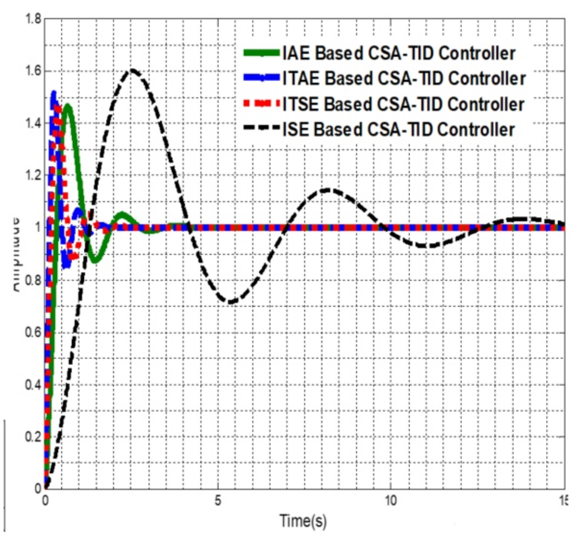

Figure 7: Step Response of CSA-TID controller with different performance indices

The effectiveness of the controllers is quite evident from the stable response of the system. To further, investigate the transient and steady-state performance of CSA-TID and CSA-I-TD controllers a comparison of t_r, t_s, e_{ss}, and % OS is given in Table 5.

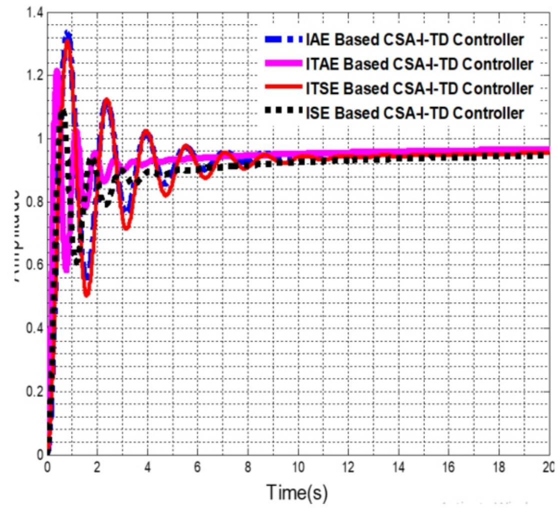

Figure 8: Step Response of CSA-I-TD controller with different performance indices

Table 5: Performance comparison of CSA based TID and I-TD controllers

Performance Index	Controller	Rise Time (t_r) (sec)	Steady State error (e_{ss})	Settling Time (t_r) (sec)	% Overshoot (% OS)
IAE	TID	0.254	0	1.77	31.79
	I-TD	0.34	4%	9.76	25
ITSE	TID	0.14	0	1.04	32.16
	I-TD	0.36	4%	14.28	23.66
ITAE	TID	0.108	0	1.05	33.99
	I-TD	0.18	4%	7.56	17.69
ISE	TID	0.92	0	11.62	37.58
	I-TD	0.32	5%	18.8	8.68

From the results of Table 5, it is cleared that CSA-TID controller with each performance index eliminates the steady state error with each performance index by giving minimum rising and settling times but gives additional % OS as compared to CSA-I-TD controller. Conversely, CSA-I-TD controller undergoes some steady state error (within 5%) with more settling time but less % overshoot as compared to CSA-TID controller.

VII. CONCLUSIONS

The performance comparison of the fractional order TID and I-TD have been evaluated for the stability control of MLS. Cuckoo Search Algorithm and Teaching Learning Based Optimization based on various performance indices (ISE, ITSE ITAE and IAE,) have been employed to optimize controller parameters. The simulation results show the overall efficacy of proposed controllers in stabilizing the system. It is clear from the results that TLBO and CSA based TID controller based on each performance index completely eliminates the steady state error. ITSE based TLBO-TID controller minimizes the rise time to 0.04sec and settling time to 0.47 sec. Furthermore, ISE based CSA-I-TD controller achieves minimal rise time of 0.32 sec and 8.6% overshoot. It can be concluded from the results that TID and I-TD controllers are handy for stability and satisfactory transient and steady-state performance of the Magnetic Levitation System in terms of rising time, settling time, overshoot and steady state error.

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