Journal of Scientific & Industrial Research
Vol. 80, April 2021, pp. 322-327

A Comparative Performance Assessment of Evolutionary Fractional Order PID Controllers for Magnetic Levitation Plant with Time Delay

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Received 24 August 2020; revised 17 February 2021; accepted 24 March 2021

Fractional Order controllers have been extensively applied to various fields of science and engineering, since several decades, because of the ability to control more parameters and consequent better control. However, to achieve this advantage, proper tuning of the associated parameters plays an important role. To achieve this objective, this paper employs a multi-agent symbiotic organisms search (MASOS) algorithm for appropriately tuning the parameters of fractional order proportional-integral-derivative (FOPID) controller for stabilizing a magnetic levitation plant (MLP) with time delay. Three different FOPID controllers have been precisely tuned and their performance has been evaluated and compared in this paper. The results demonstrate that the I-PD configuration produces the best performance in terms of time domain as well as frequency domain specifications, when compared with the other configurations.

Keywords: Degree of freedom, Evolutionary algorithm, Open-loop unstable system, Robustness, Sensitivity

Introduction

Recent years have witnessed a surge in the application of FOPID controllers in several areas of science and engineering, such as control of power system, nonlinear complex systems, unmanned aerial vehicles, etc.[1–4] The transfer function of FOPID controller is defined as Eq. (1):

$$G(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \qquad \dots (1)$$

The FOPID controller has five parameters: three gains and two non-integer orders, which may be tuned to achieve the desired performance. Since there are a greater number of tunable parameters, an FOPID controller provides better control over the system, and helps in achieving a greater number of desired specifications, than a standard PID controller. It has been established, after several applications and results, that an FOPID controller work better for both integer-order and fractional-order plants, nonlinear plants and plants with uncertainty.[5,6] However, due to extra number of parameters, tuning an FOPID controller is complex, because the dimension of the optimization problem has increased. It is observed that the optimization algorithms which explore the search space in a decentralized fashion are better for solving high dimension optimization problems.

This work applies a heuristic algorithm, namely, multi agent based symbiotic organisms search (MASOS) for tuning the parameters of FOPID controller, by solving an optimization problem formulated for this purpose. The designed FOPID controller has been applied to stabilize an MLP with time delay, which is a second order open loop unstable plant. The contributions of this research work are: 1) design of a fractional order I-PD controller for a time delay magnetic levitation plant, 2) formulation of a constrained objective function based on frequency domain specifications, which when minimized will guarantee robust closed loop performance, 3) application of multi agent based evolutionary algorithm to solve the optimization problem and 4) assess the optimized closed loop system for robustness against external disturbance and measurement noise.

Magnetic Levitation Plant (MLP)

The MLP considered for this work is a hardware setup provided by the Feedback Instruments Ltd.[7] The image of the experimental setup and schematic diagram and of MLP is illustrated in Fig. 1a and 1b, respectively. It is an electromechanical system

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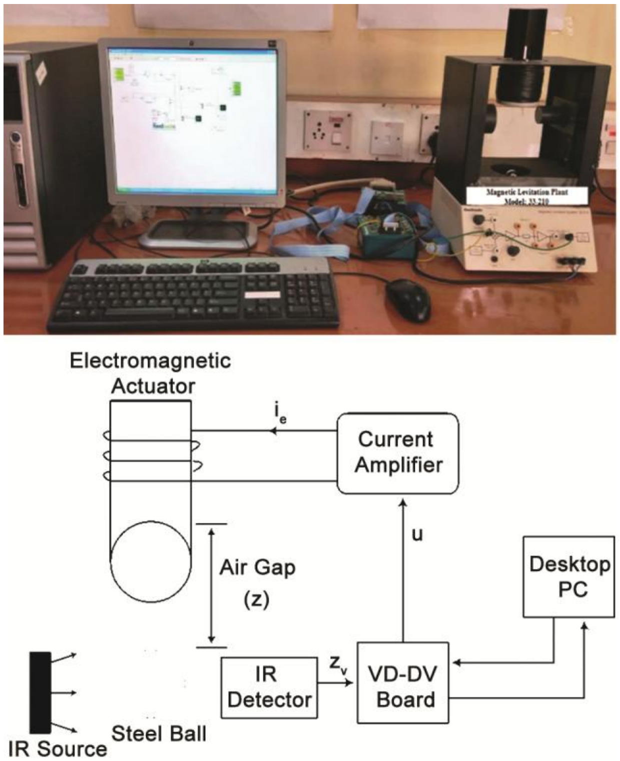

Fig. 1 — (a) Experimental setup of MLP, (b) Schematic diagram of MLP

consisting of a metallic ball suspended in air, using magnetic forces generated by an electromagnet. The dynamic of the MLP is governed by:

$$m\ddot{z} = mg - k\frac{{i_e}^2}{z^2} \qquad \ldots (2)$$

where, m represents mass of the ball, z signifies the distance of the ball from the electromagnet, i_e is the excitation current, k is a constant depending on some parameters of the MLP system, and g is the acceleration due to gravity. It is obvious that Eq. (2) is a nonlinear system.

The transfer function of MLP, after linearization and substitution of parameters from manual[7] is expressed in Eq. (3). The authors advise the reader to refer the previous work[8,9] for the detailed mathematical model of the MLP.

$$G_p(s) = \frac{-3518.85}{s^2-2180} \qquad \ldots (3)$$

To realize real time conditions, time delay has been introduced into the MLP. The transfer function may, thus, be expressed as in Eq. (4). A delay of 10 msec has been used in this work, i.e., T_d=0.01 sec.

$$G_p(s) = \frac{-3518.85}{s^2-2180} e^{-sT_d} \qquad \ldots (4)$$

Multi Agent Symbiotic Organisms Search (MASOS)

MASOS is a novel optimization algorithm proposed in 2020.[10] It is a combination of multi agent system and symbiotic organisms search (SOS) algorithm.[11] Each agent, residing in the ecosystem, represent a candidate solution to the optimization problem. Each agent shares information with its local neighbors, located in a topology inspired by Von-Neumann. The *mutualism*, *commensalism* and *parasitism* operations of SOS, now, occur in small local neighborhoods of each agents. This helps in decentralizing the exploration of the search space, thereby, reducing the chances of being trapped in local optima and increasing the chances of finding the global optimum in lesser number of iterations.[10]

The MASOS algorithm consists of two operators: *Evolution* and *Cooperation*. The flowchart[10] of the algorithm is shown in Fig. 2. The evolution operator is a combination of the three above mentioned operators of SOS. However, the agents participating in these operations are from the local neighborhood, instead of the global population. In the Von-Neumann topology each agent has four neighbors. So, in evolution, an agent will participate in the operations, with any one randomly chosen agent from the four neighbors.

In cooperation operation, the neighbors of an agent having poor solution, help in improving its fitness by communicating with each other and contributing their information. This operation is analogous to the mutation operation of Genetic Algorithm (GA). For detailed description of MASOS, the reader is advised to refer to the work by Acharya and Mishra.[10]

Proposed Control Strategy

The parameters of the FOPID controller have been tuned using the MASOS algorithm. Initially, the 1-DOF structure has been tuned. Subsequently, the same parameters have been used to implement the 2-DOF and I-PD configurations. For more details on the 2-DOF structure refer to the work by Ghosh *et al*.[8] In other words, values of the controller gains remain same for all the structures. The objective function chosen for the purpose is defined below.

$$J(K_p, K_i, K_d, \lambda, \mu) = min\left\{\frac{d}{d\omega}\angle L(j\omega_{gc})\right\} \qquad \ldots (5)$$

Subject to the following constraints:

$$|L(j\omega_{gc})| = 0dB$$
$$\angle L(j\omega_{gc}) = \pi + PM$$
$$|S|_\infty < 2$$
$$|T|_\infty < 2$$
$$e_{ss} = 0$$

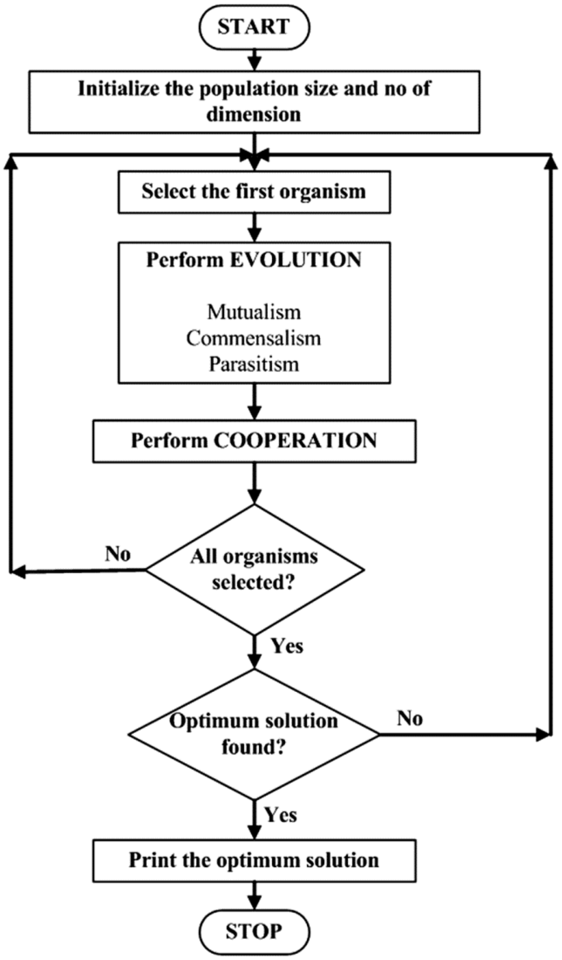

Fig. 2 — Flowchart of MASOS[10]

where, $L(j\omega)$ is the frequency response of the loop transfer function, ω_{gc} is the gain cross-over frequency expressed in rad/s, PM is the phase margin expressed in degrees, $|S|_\infty$ is the infinity norm of the sensitivity function, $|T|_\infty$ is the infinity norm of the complementary sensitivity function and e_{ss} is the steady state error of the system. The objective is to minimize the slope of the phase curve of the loop transfer function, at the gain cross-over frequency. This will result in a flat phase curve in the vicinity of gain cross-over frequency, ensuring that the phase margin of the system remains unaffected even if there is any variation in the system gain. Also, the overshoot in the response of such a system remains constant for changes in system gain due to variation in system parameter. This property is called *iso-damping*.[9]

The first two constraints ensure that the gain and phase conditions are upheld. The next two constraints guarantee that the infinity norms of the sensitivity and complementary sensitivity functions are less than two. This helps in achieving decent robustness to external disturbances and noise.[8] The last constraint ensures zero steady state error, guaranteeing accurate reference tracking. Using all these constraints help in searching only those solutions which make the system robust and accurate.

Results and Discussion

The objective function as in Eq. (5) has been solved using MASOS. All the simulations have been executed in MATLAB 2018a Simulink on a desktop PC equipped with intel core i7 processor and 8GB RAM. The script for the MASOS algorithm has also been executed on the same desktop PC. The objective function, along with the constraints, has been defined as a user-defined function (UDF) in the MATLAB environment. This UDF has been called in the MASOS algorithm, for optimization purpose. The MASOS algorithm has been executed for 30 independent runs. The maximum iteration count of the algorithms has been kept at 1000 and the ecosystem size (E_{size}) is chosen to be 7, making the population size equal to 49 (population size = $E_{size}\times E_{size}$). The result of MASOS is shown in Table 1. The optimum values of the controller parameters are listed in the table. All the structures, namely, 1-DOF, 2-DOF and I-PD, have been implemented using these values. The time domain specifications of the compensated system are shown in Table 2.

Time Domain Analysis

It has been observed that the 1-DOF structure exhibits excess overshoots, which makes it practically infeasible for implementation. The large overshoots occur due to the presence of the controller zeros in the forward path of the closed loop system. The 2-DOF and I-PD structures help in overcoming this problem. Since the controller zeros are removed from the forward path in the 2-DOF and I-PD configurations, these structures exhibit minimized or without any overshoot. It can be seen from the Table 2, that in comparison to the 2-DOF configuration, the I-PD structure reduces the overshoot by 16% and causes an improvement of 69% in the speed of response by reducing the settling time. The corresponding system response is shown in Fig. 3. Inset presents a clear view, to facilitate the comparison between the different responses. It is clear that the system exhibits too much overshoot with 1-DOF structure and the closed loop response contains the least overshoot and oscillations when used with the I-PD configuration.

Frequency Domain Analysis

The frequency domain specifications of the compensated system are listed in Table 3. It is observed that, even if the Gain Margin (GM) is negative for 1-DOF and 2-DOF structures, the overall closed loop system is stable. This is so because the definition of GM to be positive, holds true for open loop stable systems. However, for open loop unstable systems, such as the MLP, the GM may be negative even is the system is stable. From the table it is observed that the closed loop system exhibits the best frequency domain behaviour with the I-PD structure, when both the GM and PM are positive.

Table 1 — Result of MASOS

K_p	K_i	K_d	λ	μ
−0.778	−4.87	−0.0377	0.815	0.895

Table 2 — Time domain specifications and fitness value

Controller	Overshoot (%)	Settling Time (sec)	Rise Time (sec)	J (degrees/rad/s)
1-DOF	283.8	0.652	0.008	−0.00084
2-DOF	31.97	1.253	0.0346	0.00063
I-PD	26.78	0.392	0.039	0.00021

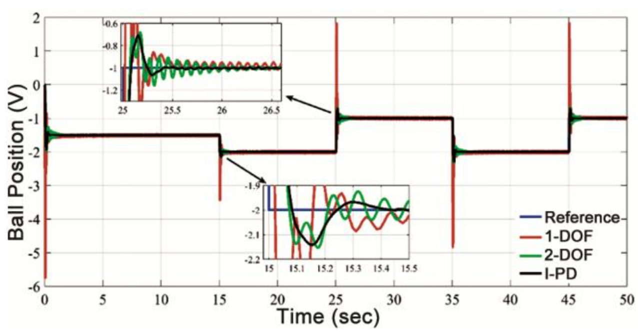

Fig. 3 — Comparison of the responses of MLP with various controllers

It also becomes obvious from the last column of Table 3, that the I-PD structure, with the lowest slope of phase curve, can achieve the iso-damping property in the best way, when compared to the other two structures.

In Fig. 4 the bode plots of the MLP with different controller configurations is illustrated. Here, it is important to point out that the closed loop transfer function of the system with both 1-DOF and 2-DOF controller structures remain the same. So, for same set of controller parameters, the frequency response of the both the controller configurations remain the same. Hence, they superimpose over each other. It is worthwhile to note in the figure that the phase plot for all the controller configurations is flat near the gain cross over frequency, which is the ultimate objective of the optimization problem defined in Eq. (5). It is, thus, verified that the closed loop system achieves the iso-damping property.

Robustness to External Disturbance and Measurement Noise

To investigate the performance of the controllers, the system is subjected to external disturbance. A pulse signal of amplitude 0.02V and time period 10 sec is introduced into the system at the output port. The performance of the 2-DOF and I-PD structures in rejecting the effects of the disturbance signal are compared in Fig. 5. It has been observed that the 2-DOF configuration removes the disturbance in nearly 0.8 seconds, whereas the I-PD structure takes only 0.4

Table 3 — Frequency domain specifications

Controller	ω_g (rad/s)	ω_p (rad/s)	GM (dB)	PM (degrees)	J (degrees/rad/s)
1-DOF	62.2	22.3	−2.58	15.9	−0.00084
2-DOF	62.2	22.3	−2.58	15.9	0.00063
I-PD	20.3	53.1	9.57	39	0.00021

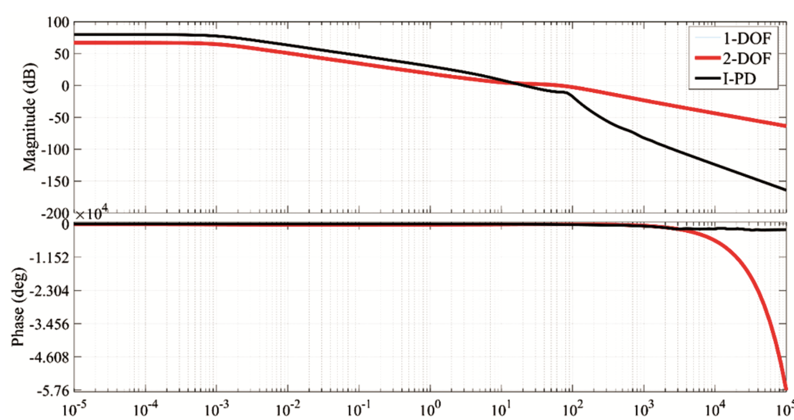

Fig. 4 — Comparison of the frequency responses of MLP

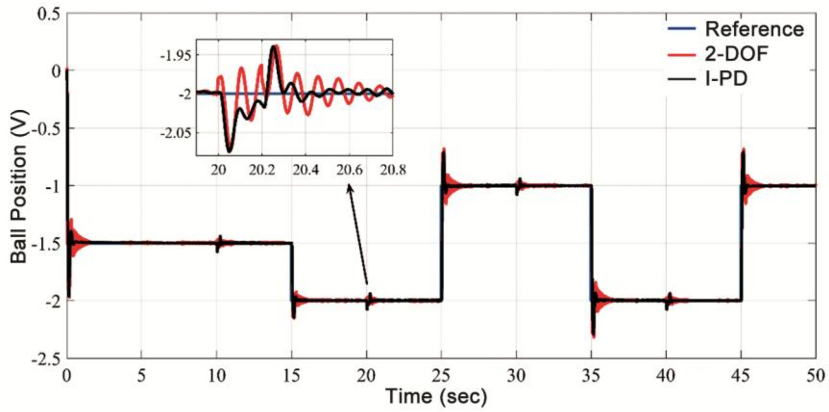

Fig. 5 — Comparison of the disturbance rejection performance

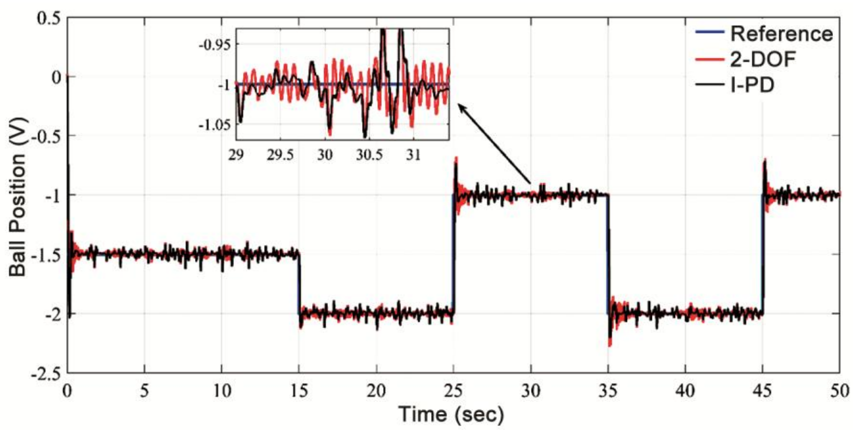

Fig. 6 — Comparison of the disturbance and measurement noise rejection

seconds. It is, therefore, verified that the I-PD controller exhibits better robustness to external disturbance.

The performance of the controllers is also tested when the system was subjected to measurement noise along with external disturbance. For the purpose, a band limited white noise of 10^{-6} dB power is added to the previously applied pulse signal. In Fig. 6 a comparison of the system responses with the different controller configurations is presented. Looking at the inset inside the figure, it becomes evident that the system's response is more stable having less oscillations, when used with I-PD controller.

Conclusions

The MASOS has been applied for precise tuning three structures of FOPID controller for stabilizing MLP with time delay. The tuning of the controller is achieved by minimization of an objective function, using MASOS, which finally improves the robustness and iso-damping property for the system. Three controller configurations, such as, 1-DOF, 2-DOF and I-PD have been implemented using proper approach and the performance of these structures have been compared with each other. It is observed that the I-PD structure helps in reducing the overshoot and settling time of the system response. Also, the I-PD configuration helps in improving GM and PM, which are associated with the stability of the closed loop system. To further check for robustness, the MLP has been subjected to external disturbance and measurement noise. The results of the study confirm that the I-PD configuration provides the best possible robustness to the closed loop system, by suitably eliminating the disturbance and in suppressing the noise quickly. In essence, the proposed FOI-PD system outperforms the other configurations by providing better time domain as well as frequency domain performance.

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