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PID/IPD Controller Design For Electro Mechanical Systems – A Study With PSO, BFO And FA

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***Abstract:** In this work, PID and modified form of PID (I-PD) controller design procedure is proposed for highly non-linear benchmark electromechanical systems such as Vehicle Active Suspension System (VASS) and Magnetic Suspension System (MSS) discussed in the literature. The proposed controller design is implemented using the most successful heuristic algorithms, such as Particle Swarm Optimization (PSO), Bacterial Foraging Optimization (BFO) and Firefly Algorithm (FA). A weighted sum of objective function comprising the overshoot (Mp), settling time (Ts), integral square error (ISE) and integral absolute error (IAE) is chosen to guide the heuristic search in order to find the controller parameters such as Kp, Ki, and Kd. In the proposed work, the major aim is to compare the performance of the considered heuristic algorithms for the controller design problem. The simulation work is implemented using the Matlab software and the performance of this study is validated using Mp, Ts, ISE and IAE values for the reference tracking and disturbance rejection operations. This study confirms that, FA offers faster convergence compared with the PSO and BFO algorithms.*

***Keywords:** PID controller, Heuristic algorithms, Vehicle active suspension system, Magnetic suspension system.*

1. Introduction

Controllers are very famous in closed loop system in order to achieve the desired performance based on the setpoint value. In the recent years, due to its simplicity, reputation and easy implementation, PID and modified forms of PID controllers are extensively used in industries and laboratories. Literature also evident that, heuristic algorithm based PID controller design is very popular among the researchers to discover optimal solutions for a class of linear and non-linear systems [1-8]. Even though a extensive quantity of algorithms are existing in the literature, selection of a particular algorithm to solve the considered optimization problem chiefly relies on the following factors : (i) The search dimension; (ii) Convergence speed of heuristic algorithm, (iii) Precision in optimization, and (iv) Number of initial algorithm parameters to be allocated.

The existing controller design problem in the literature for the stable and the linear system are very simple compared with the unstable and the non-linear systems. The number of traditional controller design procedure existing for the unstable and non-linear systems are very few [9]. Hence, recently heuristic algorithm based PID and IPD [10,11], fractional order PID and setpoint weighted PID controller design procedures are widely proposed by the researchers for a class of systems.

From the resent literature, it is noted that, heuristic algorithms such as Particle Swarm Optimization (PSO), Bacterial Foraging Optimization (BFO) and Lévy flight based Firefly Algorithm (FA) are widely adopted to solve a variety of engineering optimization problems. The PSO is used to design the PID controller for a class of stable and unstable systems [12]. The enhanced BFO algorithm is used to design the PID/IPD controller for highly unstable systems [10]. The FA based approach is considered to design the PI/PID controller for Single Input and Single Output (SISO) and Multi Input and Multi Output (MIMO) systems [8].

In this paper, PSO, BFO and FA is considered to design the PID and IPD controller for the highly non-linear electromechanical systems, such as Vehicle Active Suspension System (VASS) [13,14] and Magnetic Suspension System (MSS) [9,15]. The major aim of this work is to design an optimal controller for the considered process and to provide a detailed analysis among the considered algorithms based on the algorithm performance and the process performance values, such as M_p, T_s, ISE and IAE.

This paper is organized as follows: Section 2 presents the overview of the electromechanical systems considered in this paper and the details of the heuristic algorithms adopted in this study and its implementation are discussed in section 3. Section 4 depicts the simulated results and the discussion with the optimally designed PID and IPD controller. The conclusion of the present research work is discussed in Section 5.

2. System description

In order to implement the heuristic algorithm based PID/IPD controller, the following non-linear electromechanical systems are considered:

2.1 Vehicle Active Suspension System

In vehicles, a good suspension should provide a comfortable ride and good handling within a reasonable range of deflection. In active suspension system, a closed loop electromechanical circuit is used to provide the comfortable ride irrespective of the road conditions. In this paper, a quarter car model of VASS existing in the literature is considered.

A detailed description of the VASS and its control can be found in [13,14]. The state-space model of the VASS is presented in Eqn. (1).

$$\begin{bmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \\ \dot{X}_4 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \\ -\frac{K_a}{M_2} & 0 & -\frac{C_a}{M_2} & \frac{C_a}{M_2} \\ -\frac{K_a}{M_1} & \frac{K_t}{M_1} & -\frac{C_a}{M_1} & \frac{C_a}{M_1} \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{bmatrix} + \quad (1)$$

$$\begin{bmatrix} 0 \\ 0 \\ \frac{1}{M_2} \\ -\frac{1}{M_1} \end{bmatrix} U_a + \begin{bmatrix} 0 \\ -1 \\ 0 \\ 0 \end{bmatrix} \dot{r}$$

where U_a is the control force and r is the road displacement.

Table 1: Nominal parameters of VASS

PARAMETERS	SYMBOLS	QUANTITIES
Body mass	M2	250 Kg
Wheel mass	M1	50 Kg
Stiffness of the body	Ka	16 K N/m
Stiffness of the	Kt	160 K N/m
Stiffness of the	Ca	1.5 K N.s/m

2.2 Magnetic Suspension System

MLS is an electro-mechanical system and the construction detail is depicted in Fig 1. In this system, a controller is used to regulate the electric current (i) until the electromagnetic force (f) equals to the weight of the steel ball (m*g). When the above condition is reached, the ball will levitate in an equilibrium state [9,15]

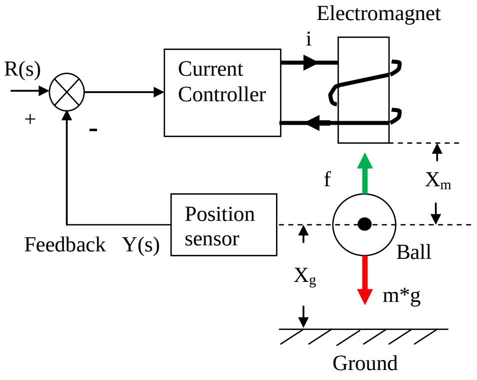

Fig. 1 Construction of Magnetic Levitation System

The mathematical model of the MLS is described below;

Voltage applied to the coil : $V(t) = R\, i(t) + L \frac{d\, i(t)}{dt}$

(2)

Force by the electromagnet is : $f(x,i) = c\left(\frac{i}{x}\right)^2$; and

$$c = \frac{L_0 X_0}{2} \quad (3)$$

Mechanical force on the ball

$$: m \frac{d^2 x}{dt^2} = (m * g) - c\left(\frac{i}{x}\right)^2 \, (4)$$

Where x = X_m is the distance between ball and magnet, i = current through coil, L = inductance of the coil, R= internal resistance of the coil, m= mass of the ball, g = acceleration due to gravity, L_0 is the additional inductance of the magnetic coil due to the ball placed at the equilibrium position x_0.

From Eqn. 5, coil inductance (L) is a nonlinear function and it is a function of ball position x.

The approximate inductance is $L(x) = L + \frac{L_0 x_0}{x}$ (5)

Linear form of Eqn.4 can be written as ;

$$m\frac{dx^2}{dt} = -c\left(\frac{i_0}{x_0}\right)^2 \left\{1 + 2\left[\frac{i(t)}{i_0} - \frac{x(t)}{x_0}\right]\right\} + mg \qquad (6)$$

When $c\left(\frac{i_0}{x_0}\right)^2 = m * g$, Eqn.6 can be written as:

$$m\frac{dx^2}{dt} = -\frac{2i_0 c}{x_0^2} i(t) + \frac{2{i_0}^2 c}{x_0^3} x(t) \qquad (7)$$

In Eqn.7, x(t) and i(t) are the incremental displacement and incremental magnet current around their nominal values x_0 and i_0. The linearized state model of the system around the point $x_1 = x_{01}$ is presented below;

The state vector for the system is $X_0 = [x_{01} \;\; x_{02} \;\; x_{03}]^T$ (8)

At equilibrium, $x_{02} = 0$ and $x_{03} = x_{01}\sqrt{\frac{mg}{c}}$.

(9)

The linearized state model of the system is;

$$A = \begin{bmatrix} 0 & 1 & 0 \\ \frac{Cx_{03}^2}{Mx_{01}^3} & 0 & -2\frac{Cx_{03}}{Mx_{01}^2} \\ 0 & 2\frac{Cx_{03}}{Lx_{01}^2} & -\frac{R}{L} \end{bmatrix} \; ; \; B = \begin{bmatrix} 0 \\ 0 \\ 1/L \end{bmatrix} \; ;$$

$$C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$

(10)

The MLS parameters are assigned as m = 0.05kg, g = 9.81 m/s2, L = 0.01H, R = 1Ω, C = 0.0001, x01 = 0.012 M, x02 = 0 M/s, and x03 = 0.84A [21].

The mathematical model of the considered MLS is represented in eqn.11 and this model is considered during the controller design procedure.

$$A = \begin{bmatrix} 0 & 1 & 0 \\ 1633.33 & 0 & -23.33 \\ 0 & 116.66 & -100 \end{bmatrix} \; ; \; B = \begin{bmatrix} 0 \\ 0 \\ 100 \end{bmatrix} \; ;$$

$$C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix}$$

(11)

3. Heuristic algorithms

In this work, heuristic algorithms such as Particle Swarm Optimization (PSO) and Firefly Algorithm (FA) are considered to validate the performance of TLBO.

3.1 Particle Swarm Optimization

PSO is developed by modeling the group activities in flock of birds or school of fish. Due to its high computational capability, it is widely considered by the researches to solve constrained and unconstrained optimization problems. In this work, PSO with the following mathematical expression is considered [6,16]:

$$V_i(t+1) = W^t . V_i^t + C_1 R_1 (P_i^t - S_i^t) + C_2 R_2 (G_i^t - S_i^t)$$

(12)

$$X_i(t+1) = X_i^t + V_i(t+1)$$

(13)

where w^t is inertia weight (chosen as 0.7), R_1 and $R_2$are random values [0,1], C_1 and C_2 is allotted as 2.0 and 1.6 correspondingly.

3.2 Bacterial Foraging Optimization

Bacterial Foraging Optimization (BFO) algorithm is one of the successful nature inspired heuristic method, developed based on the mathematical model of the foraging activities in Escherichia coli (E.coli) bacteria. In this work, the enhanced BFO algorithm discussed in [10] is adopted.

The initial BFO parameters are assigned as follows:

$$N = 20;\ N_c = \frac{N}{2};\quad N_s = N_{re} \approx \frac{N}{3};\quad N_{ed} \approx \frac{N}{4};\quad N_r = \frac{N}{2};\quad P_{ed} = \left(\frac{N_{ed}}{N+N_r}\right);\ d_{attract} = W_{attract} = \frac{N_s}{N};$$

$$\text{and}\ \ h_{repell} = W_{repell} = \frac{N_c}{N} \tag{14}$$

3.3 Firefly Algorithm

FA based technique utilizes the mathematical representation of a firefly, searching for a mate in the assigned search space. The detail of FA can be found in [17-20]. The association of an attracted firefly towards a mate can be expressed as:

$$X_i^{t+1} = X_i^t + \beta_0 e^{-\gamma d_{ij}^2} (X_j^t - X_i^t) + \alpha^1 (rand - ½) \tag{15}$$

where X_i^t is early location; X_i^{t+1} is updated location; $\beta_0 e^{-\gamma d_{ij}^2} (X_j^t - X_i^t)$ is attraction among fireflies; β_0 is preliminary attractiveness; γ is absorption coefficient; α^1 is randomization operator and rand is random number [0,1]. In this paper, the following values are chosen for FA parameters: $\alpha^1 = 0.15$; $\beta_0 = 0.1$ and $\gamma = 1$.

3.4 PID/IPD controller

An industrial controller naturally available as a packaged form and to perform well with the industrial process problems, these controllers requires optimal tuning. In this paper, parallel form of PID / IPD controller structure is considered as shown below. A low pass filter is used with the derivative term to reduce the effect of measurement noise. The PID structure is defined below [9,10]:

$$G_C(s) = K_p \left[1 + \frac{1}{T_i\, s} + \frac{T_d\, s}{\frac{T_d s}{N} + 1} \right] \tag{16}$$

where K_p / T_i = K_i, $K_p * T_d$ = K_d, N = filter constant = 10.

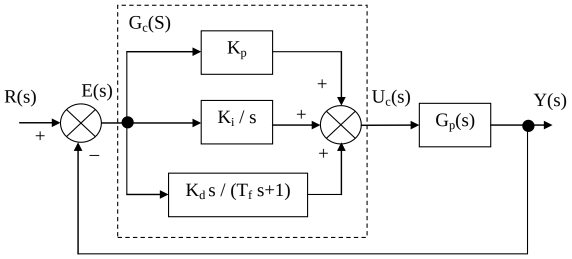

Fig. 2 Parallel PID structure

IPD (I-PD) controller is a modified form of the classical PID controller. In this integral part is placed in the forward loop and the proportional and derivative terms are implemented in the feedback loop. This structure will offer a better result in reference tracking response [10].

3.5 Implementation

Implementation of the proposed procedure is depicted in Fig 3. The heuristic algorithm (HA) based controller design work is guided by an objective function. The heuristic algorithm will arbitrarily find the controller parameters until the objective value is satisfied.

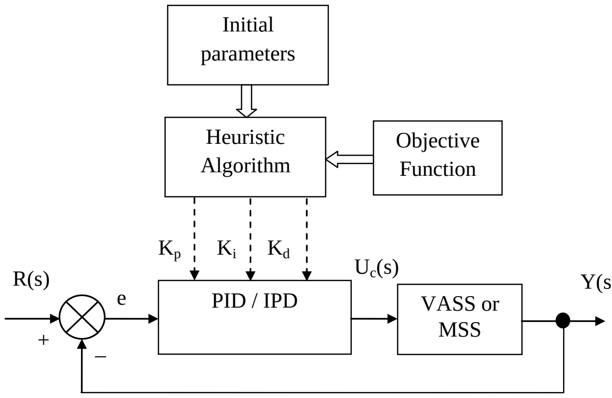

Fig. 3 Implementation of heuristic algorithm based controller design

Objective function considered in this study is presented below:

$$J_{max}(PID) = w_1 . M_p + w_2 . T_S + w3. ISE + + w4. IAE \tag{17}$$

where $ISE = \int_0^T e^2(t)dt$; $IAE = \int_0^T |e(t)|\, dt$; e – the error between the set point and process response, M_p – the overshoot, T_s- the settling time, $w_1 = w_2 = 1.5$ and $w_3 = w_4 = 2$.

The heuristic search will be terminated based on the J_{max} value and the corresponding K_p, K_i and K_d are displayed as the optimal controller parameters.

4. **Results and Discussions**

This section presents the results obtained with the simulation study implemented in Matlab 2010a software. During this study, the following algorithm parameters are assigned: number of agents (*N*) is chosen as 20, number of iteration is chosen as 500, the dimension of search (*D*) is assigned as 3 and the algorithm is allowed to search the controller parameters till the J_{max} is reached. This controller design procedure is repeated 10 times and the mean value is chosen as the optimal controller parameter.

Initially, the controller design procedure is implemented on the non-linear VASS model discussed in [13,14] using the PSO algorithm. Firstly, the PID design is implemented for this system and the average CPU time (using Matlab's Tic-Toc function) is found to be 108.94 sec. Similar procedure is implemented using the BFO and FA algorithms and the average CPU time is obtained as 112.15 sec and 98.04 sec respectively. The controller parameter values and its performance measure are shown in Table 2.

Initially the reference tracking response of VASS is studied. Later the load disturbance response is studied with a disturbance value of 0.5 (50% of the setpoint) applied at 400 ms. The numerical values of the performance measures are presented in Table. 2 and the graphical value are depicted using Fig. 4 and Fig.5. From this table, it can be noted that, the FA based approach offers better T_s, ISE and IAE for the reference tracking and the disturbance rejection compared with the alternatives.

From Fig 4, it can be noted that, the overshoot and the settling time offered by the PID controller is more. Hence, in order to improve the performance, the I-PD controller is implemented for the considered electromechanical systems. Initially, the I-PD controller is designed for the VASS system and the average CPU time is obtained as follows; PSO ased search = 71.28 sec; BFO based search = 91.64 sec and the FA based search 69.47 sec.

The optimized I-PD controller values for the VASS and the MSS are presented in Table.3 and the corresponding performance values for the reference tracking and the disturbance rejection operations are presented. From this table, one can observe that, the overall performance of the BFO algorithm is better for the VASS compared to the PSO and FA. For the MSS, PSO tuned IPD offers better reference tracking and the BFO tuned IPD offers better disturbance rejection operation. Even though the performance values are better, the FA offers the faster convergence due to its Lévy flight search strategy.

Fig. 6 shows the reference tracking response of the VASS and Fig. 7 depicts the disturbance rejection performance for a disturbance value of 0.5 offered at 150 ms. Fig.8 shows the disturbance rejection operation of MSS for a disturbance signal of o.1 applied at 30ms. Fom these results, it can be observed that, the HA tuned PID/IPD controller offers better result on the considered electromechanical systems.

Table. 2 PID Controller parameters and its performance values for VASS

HA	K_p	K_i	K_d	Reference tracking				Disturbance rejection	
				M_p	T_s	ISE	IAE	ISE	IAE
PSO	38.1360	1.4501	41.3974	**0.178**	137.5	3.926	12.51	4.901	18.76
BFO	36.8376	2.5402	37.6584	0.221	192.2	4.134	14.47	5.162	21.68
FA	41.3995	1.8195	39.1837	0.201	**135.7**	**3.841**	**12.49**	**4.795**	**18.72**

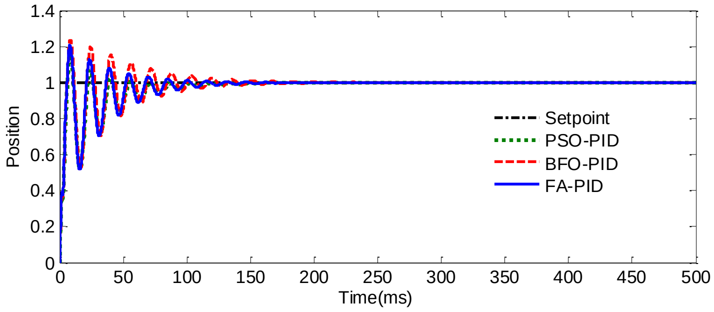

Fig. 4 Reference tracking response of VASS

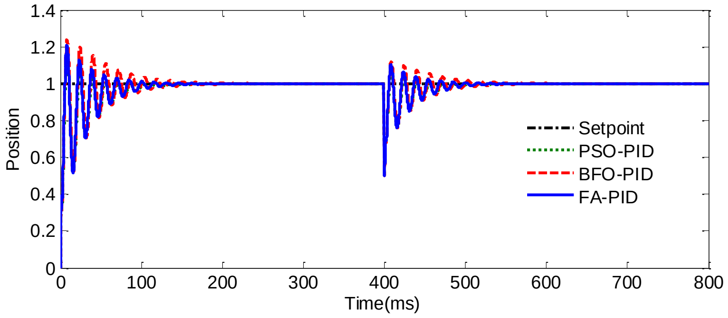

Fig. 5 Disturbance rejection response of VASS

Table 3. IPD Controller parameters and its corresponding performance values

	HA	K_p	K_i	K_d	Reference tracking				Disturbance	
					M_p	T_s	ISE	IAE	ISE	IAE
VASS	PSO	38.136	2.817	52.9226	0	92.3	10.2	19.2	11.0	24.0
	BFO	36.944	3.399	49.0065	0	**74.0**	**8.52**	**15.7**	**9.41**	**21.6**
	FA	37.771	3.164	53.2746	0	79.2	9.21	17.0	10.0	22.0
MSS	PSO	-	-	-4.5003	0	**5.34**	1.32	**2.08**	**2.05**	**3.84**
	BFO	-	-	-4.4173	0	5.90	**1.31**	2.16	1.82	3.67
	FA	-	-	-4.5830	0	13.2	1.75	3.13	2.19	4.81

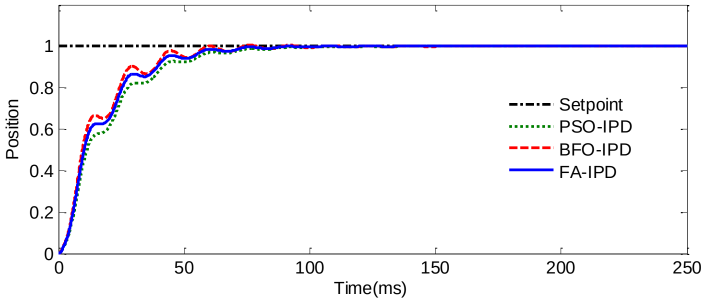

Fig. 6 Reference tracking response of VASS for IPD controller

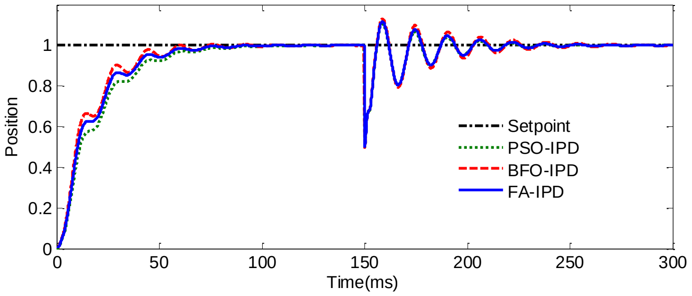

Fig. 7 Disturbance rejection response of VASS with IPD controller

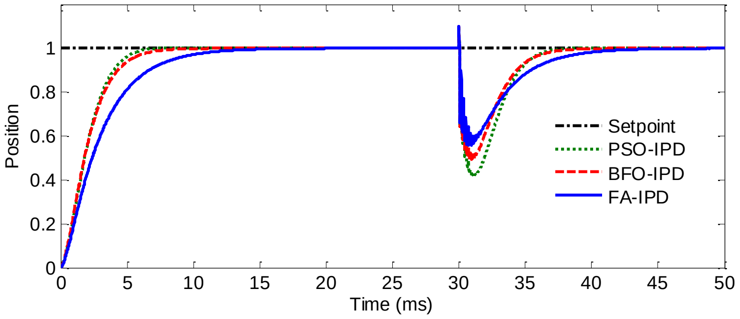

Fig. 8 Disturbance rejection response of MSS with IPD controller

5. Conclusions

In this work, design of PID/IPD controller is proposed for electromechanical systems, such as Vehicle Active Suspension System and Magnetic Suspension System using heuristic algorithms. In the proposed work, a weighted sum of objective function is considered and maximization of this objection function is chosen as the stopping criteria for heuristic search. The proposed work is implemented using the Matlab software. The simulation study is carried out for the reference tracking and disturbance rejection operations. From this study, it is observed that, the FA algorithm offers better convergence for the PID and IPD search. The reference tracking performance of VASS with the PID controller is better than the PSO and BFO algorithm. The IPD controller tuned with the PSO offers better reference tracking on the VASS and the BFO algorithm offers better performance on the disturbance rejection for the MSS.

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