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TECHNICAL PAPER

Application of stochastic fractal search in approximation and control of LTI systems

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Abstract

The present work deals with the application of evolutionary computation in approximation and control of linear time invariant (LTI) systems. Stochastic fractal search algorithm (SFS) has been proposed to obtain low order system (LOS) from LTI higher order system (HOS) as well as in speed control of DC motor with PID controller. SFS is quite simple to use in control system and employs the diffusion property present in random fractals to discover the search space. In approximation of LTI systems, the integral square error (ISE) while in control of DC motor, the integral of time multiplied absolute error has been taken as an objective/fitness functions. In system's approximation, the results show that the proposed SFS based LOS preserves both the transient and steady state properties of original HOS. The simulation results have also been compared in terms of; ISE, integral absolute error and impulse response energy with well known familiar and recently published works in the literature which shows the superiority of SFS algorithm. In control of DC motor, the obtained results are satisfactory having no overshoot and less rise and settling times in comparison to existing techniques.

1 Introduction

The large scale systems are all around and exist in diverse fields such as, complex chemical processes, biomedical systems, socio-economic systems, transportation systems, ecological systems, electric power systems, aeronautics, hydraulic, pneumatic, thermal, mechanical, environment systems, etc. or a combination of these. A system is said to be large if it can be decoupled or partitioned into a number of interconnected systems or small scale/micro systems for either computational or practical reasons. The analysis of such physical systems starts by building up of a model which may be considered as a faithful representation of such systems. The task of a control engineer begins with the formulation of a model. The rest of the analysis and design can be done with this model.

Whether existing or to be designed, when a system is mathematically modelled for analysis and improvement, initially a complex model of high order is obtained. So, if the order of the system modelled is high then it may pose difficulties in its analysis, synthesis and identification. An obvious method of dealing with such type of system is to approximate it by a low/micro order model which reflects the important characteristics of the original high order system such as time constant, damping ratio, natural frequency, etc. Thus approximation techniques help in understanding the system in a better way.

System's approximation eases the computational process and provides better understanding of complex systems. The literature is having various simplification and optimization techniques, such as; response matching techniques (Mukherjee et al. 2005), reduction of linear dynamic systems using error minimization technique (Mittal et al. 2004), Eigen spectrum analysis and pade approximation technique (Parmar et al. 2007a), factor division algorithm and Eigen spectrum analysis (Parmar et al. 2007b), etc. Simultaneously, the Routh approximation (Sambariya and Sharma 2016a, b), both Stability equation (Sambariya and Arvind 2016), Differentiation (Sambariya and Manohar 2016) methods have also been presented for deriving the reduced order models of the higher order systems which includes benchmark problems.

In recent years, nature inspired algorithms have been utilized in system's approximation, e.g. particle swarm

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optimization (PSO) algorithm is a member of wide category of swarm intelligence methods available in literature which is computationally useful and easier in reduced order modelling (Parmar et al. 2007c). Invasive weed optimization (IWO) which is a bio inspired numerical optimization algorithm that basically simulates natural behavior of weeds in colonizing is also available for system's approximation (Khalilpuor et al. 2011). Also, a new search method, namely Big Bang–Big Crunch (BB–BC) algorithm based on the theory of universe (Desai and Prasad 2013a, b; Biradar et al. 2016) and cuckoo search optimization and stability equation method (Narwal and Prasad 2015) are also available in literature. The application of soft computing technique (Sikander and Prasad 2015a), cuckoo search algorithm (Sikander and Prasad 2015b) and modified cuckoo search (MCS) algorithm (Sikander and Thakur 2017) have also been presented in literature in the field of system's approximation. Though, these nature inspired algorithms have great potential to obtain lower order system but unfortunately suffers from the following problems (Clerc and Kennedy 2002):

- Premature and slow speed convergence usually degrades the performance and reduces the search capability.
- The calculation directly depends upon the parameters, such as, the initial values of the control parameters, the size of swarm value, and the maximum iteration number. Dependency on large number of control parameters reduces its search capability and computational efficiency.

In the area of controllers, PID controllers are broadly used in industrial plants due to their robustness and ease of implementation. Various algorithms are available in literature to tune the parameters of PID controllers, such as; Cohen–Coon, Ziegler Nichol and Z–N step response, etc. But, all of these classical methods have some limitations (Ang et al. 2005). Further, for the control of DC motor, a comparative analysis of PID controller tuned by PSO and IWO is also available in the literature (Khalilpuor et al. 2011).

The present work deals with application of SFS in approximation and control of LTI systems. The ISE and ITAE have been taken as fitness/objective functions as per the literature which is to be minimized by proposed algorithm. The algorithm considers convergence, accuracy and exhibits comparable results (Khanam and Parmar 2017) in comparison to the recently available techniques in literature, as shown in the simulation examples.

2 Basics of DC motor

The speed control of DC motor means intentional change of the drive speed to a value required for performing the specific work. DC motor basically converts DC electric energy into mechanical energy. Speed control is also done manually by the operator or by the means of some automatic control devices. The model of DC motor and its equivalent circuit with PID controller have been shown in Figs. 1 and 2, respectively.

The parameters of the DC motor used in present study/simulation have been given (Khalilpuor et al. 2011) in Table 1.

3 Problem formulation

3.1 Approximation of LTI systems

Consider an nth order single input single output (SISO) LTI HOS system with the following transfer function:

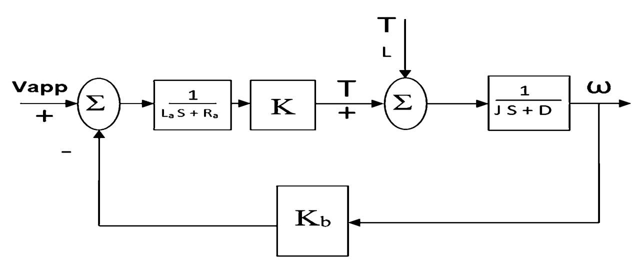

Fig. 1 Model of DC motor

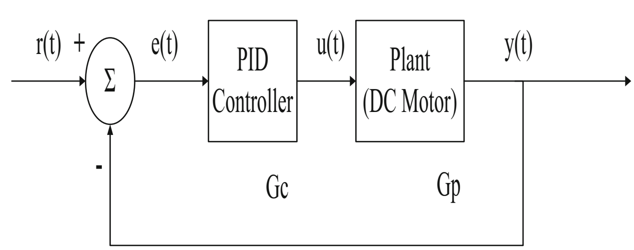

Fig. 2 Equivalent circuit of DC motor with PID controller

Table 1 Parameters of DC motor

Parameter	Value
Armature resistance; R_a	0.4 ohm
Inductance of armature winding; L_a	2.7 H
Equivalent moment of inertia of motor; J	0.0004 kg m^2
Equivalent friction coefficient of motor; D	0.0022 N m s/rad
Motor torque constant; K	15 e−3 kg m/A
Back EMF constant; K_b	0.05 s

$$G_n(s) = \frac{a_0 + a_1 s^2 + a_2 s^2 + \cdots + a_n s^{n-1}}{b_0 + b_1 s + b_2 s^2 + \cdots + b_n s^n} \quad (1)$$

Let, the rth order LOS is represented by following transfer function:

$$R_r(s) = \frac{\alpha_0 + \alpha_1 s + \alpha_2 s^2 + \cdots + \alpha_r s^{r-1}}{\beta_0 + \beta_1 s + \beta_2 s^2 + \cdots + \beta_r s^r} \quad (2)$$

where, r < n. Also, a_i , b_i , α_i and β_i are the coefficients of numerator and denominator's polynomials of HOS and LOS, respectively. Now, the aim is to obtain all the unknown parameters of LOS in (2) by minimizing the objective/fitness function (which is ISE in the present work) between the transient responses of HOS and LOS using SFS subjected to unit step input. The LOS should be a good approximation of HOS. This ISE is given by (Saraswat and Parmar 2015; Sikander and Prasad 2017b):

$$ISE = \int_0^\infty [y(t) - y_r(t)]^2 dt \quad (3)$$

The simulink model of this problem is shown in Fig. 3. The other performance indices used in this work for the purpose of comparison are given by (Parmar et al. 2007a; Sikander and Prasad 2015b):

$$IAE = \int_0^\infty |e(t)| \, dt \quad (4)$$

$$IRE = \int_0^\infty g^2(t) \; dt \quad (5)$$

3.2 Control of DC motor

In control of DC motor, the objective is that the output of DC motor should follow the set point. Therefore, PID controller has been used, which is given by:

$$G_C = K_P + \frac{K_I}{s} + K_D s \quad (6)$$

For obtaining the unknown parameters of PID controller in (6) for speed control of DC motor to ideal/set point state, fitness/objective function taken is ITAE, where error is the output velocity of DC motor. This ITAE is given by:

$$ITAE = \int_0^\infty t\,|e(t)|\,dt \quad (7)$$

The complete simulink model of DC motor with PID controller and ITAE as fitness function has been shown in Fig. 4.

Here, the objective is to obtain the unknown parameters of PID controller in (6) for speed control of DC motor to ideal/set point state by minimizing ITAE.

4 Stochastic fractal search algorithm

Stochastic fractal search (SFS) has been designed to find a heuristic or an optimal search pattern that may give a suitably superior solution to an optimization problem. SFS employs the diffusion property present in random fractals to discover the search space. It consists of two main processes; diffusion and update (Hoos and Stiitzle 2005; Salimi 2015).

The steps of the SFS algorithm are as under:

- *Initialization* First of all, the position of each particle (points) is randomly initialized depending on the problem constrains by specifying maximum and minimum bounds as:

$$P = LB + rand(UB - LB) \quad (8)$$

- *Diffusion procedure* Gaussian walk is employed to generate each point in the diffusion process. The series of Gaussian Random Walks (*GRW*) used are given by:

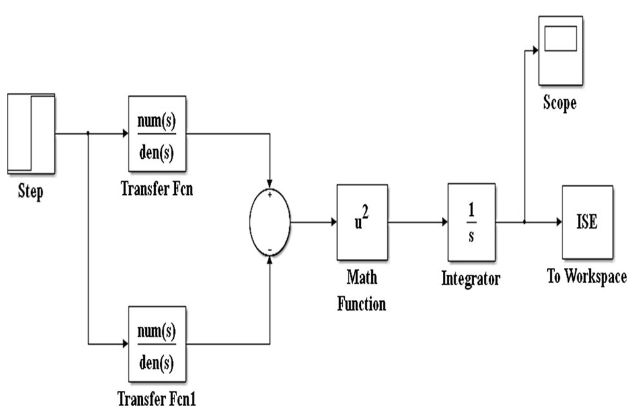

Fig. 3 Simulink model of scheme with ISE objective function

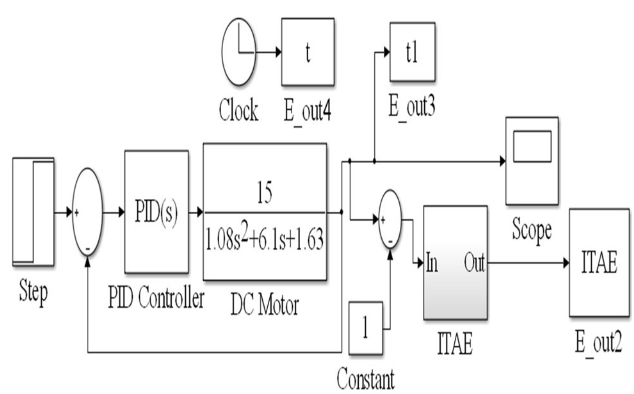

Fig. 4 Simulink model of DC motor with PID controller and ITAE objective function

$$GRW_1 = Gaussian(|BP|\ ,\ SD) + (rand \times BP - rand_1 \times P_i) \tag{9}$$

$$GRW_2 = Gaussian(|P_i|\ ,\ SD) \tag{10}$$

where, SD is the standard deviation, which is calculated as:

$$SD = \left| \frac{\log(g)}{g} \times (P_i - BP) \right| \tag{11}$$

- *Update procedure* All the particles are ranked according to the value of the objective/fitness function and each particle i is assigned a probability value given by:

$$P_{pi} = \frac{rank(P_i)}{N} \tag{12}$$

The modified position of $P_i, P_i'(j)$ is calculated as:

$$P_i'(j) = P_x(j) - \text{rand}\,[P_y(j) - P_i(j)] \tag{13}$$

All the points obtained from the above process are ranked again and a probability value is assigned as before. For a new point P_i', the current position is modified to P_i'', if the condition $P_{ai}' < rand$ is satisfied, otherwise it remains same. The points are calculated as:

$$P_i'' = P_i' - rand_g\,[P_x' - BP] | rand_g \leq 0.5 \tag{14}$$

$$P_i'' = P_i' + rand_g\,[P_x' - P_y'] | rand_g > 0.5 \tag{15}$$

The new point P_i'' replaces P_i', if the fitness value of P_i'' is better than P_i'.

Stochastic fractal search algorithm is quite simple to use in control system. The flow chart representation of the SFS algorithm is shown in Fig. 5. The flow chart describes each stage, which is performing the whole process.

The parameters used for simulation of SFS algorithm have been given in Table 2.

5 Implementation of SFS in approximation of systems

To exemplify the SFS in present work, two simulation examples of different order have been taken from the literature.

Example 1 Consider a 6th order SISO LTI HOS given by (Singh et al. 2014; Vishwakarma 2009):

$$G_6(s) = \frac{2s^5 + 3s^4 + 16s^3 + 20s^2 + 8s + 1}{2s^6 + 33.6s^5 + 155.9s^4 + 209.5s^3 + 102.4s^2 + 18.3s + 1} \tag{16}$$

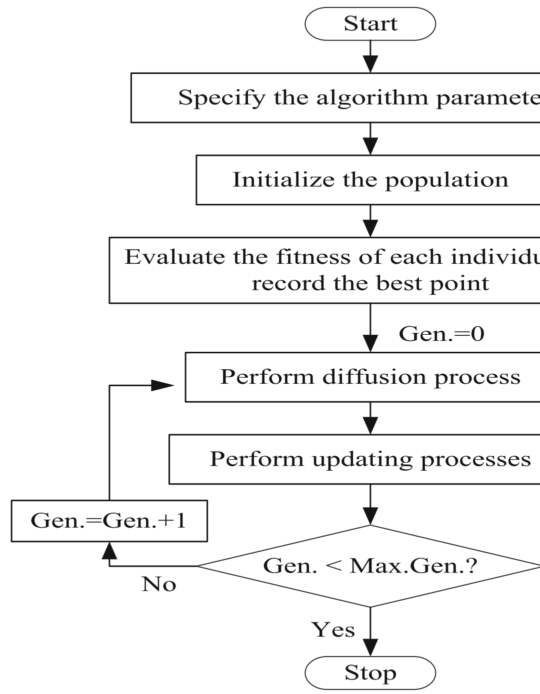

Fig. 5 Flow chart of SFS algorithm

Table 2 Parameter used for SFS algorithm

Parameter	Value
Number of search agents (population)	30
S. diffusion	2
S. walk	0.75
Maximum iterations	30
Lower bounds	[0.001 0.001 0.001]
Upper bounds	[20 20 20]

The SFS has been applied to the above system as per the scheme shown in Fig. 3 and the parameters of numerator and denominator polynomials of LOS are obtained. The SFS has been run for 30 iterations and the value of obtained ISE is 5.1534×10^{-4}. The obtained reduced denominator and numerator polynomials of LOS are:

$$D_2(s) = 4.4617s^2 + 4.7307\,s + 0.4110 \tag{17}$$

$$N_2(s) = 0.4753s + 0.4110 \tag{18}$$

Therefore, the 2nd order LOS obtained by SFS is:

$$R_2(s) = \frac{0.4753\,s + 0.4110}{4.4617\,s^2 + 4.7307s + 0.4110} \tag{19}$$

The convergence of objective function with number of iterations has been shown in Figs. 6 and 7 for the program at starting and ending. It can be seen in Fig. 7 that all the fractals/points come together to give the optimal values.

The analysis of 6th order HOS and 2nd order LOS in terms of performance indices and transient response's parameters has been shown in Table 3. It can be observed in Table 3, that the parameters of obtained 2nd order LOS by SFS are comparable with that of original 6th order HOS. Also, the SFS based LOS has lowest values of performance indices; ISE and IAE in comparison to other existing techniques and the value of IRE is closer to that of original HOS.

The comparison of responses of 6th order HOS and 2nd order LOS with other techniques has also been shown in Figs. 8 and 9. It can be observed in Figs. 8 and 9, that response of LOS by SFS has close approximation with that of original HOS.

Example 2 This simulation example has been chosen to show the superiority of SFS algorithm over other existing/available methods in the literature. Consider an 8th order SISO LTI HOS given by (Parmar et al. 2007a; Sikander and Prasad 2015a; Sambariya and Sharma 2016a):

$$G_8(s) = \frac{18s^7 + 514s^6 + 5982s^5 + 36380s^4 + 122664s^3 + 222088s^2 + 185760s + 40320}{s^8 + 36s^7 + 546s^6 + 4536s^5 + 22449s^4 + 67284s^3 + 118124s^2 + 109584s + 40320} \tag{20}$$

The SFS has been applied to the above system as per the scheme shown in Fig. 3 and the obtained reduced order denominator and numerator polynomials by SFS are:

$$D_2(s) = 0.95698\, s^2 + 6.55351\, s + 5.03619 \tag{21}$$

$$N_2(s) = 16.14315\, s + 5.03619 \tag{22}$$

Therefore, the 2nd order LOS by SFS is given by:

$$R_2(s) = \frac{16.14315\, s + 5.03619}{0.95698\, s^2 + 6.55351\, s + 5.03619} \tag{23}$$

and the value of obtained ISE is 7.033×10^{-4}. The convergence of objective function with number of iterations has been shown in Figs. 10 and 11 for the program at starting and ending.

The step and frequency responses of original 8th order HOS and SFS based 2nd order LOS have been compared in Figs. 12 and 13, respectively. It can be seen in Figs. 12 and 13, that the error gap between HOS and SFS based LOS is quite small in comparison to other existing techniques. The analysis of 8th order HOS and 2nd order LOS in terms of performance indices and transient response's parameters has also been given in Table 4, from which it can be observed that the parameters of obtained 2nd order LOS by SFS are comparable with that of original 8th order HOS.

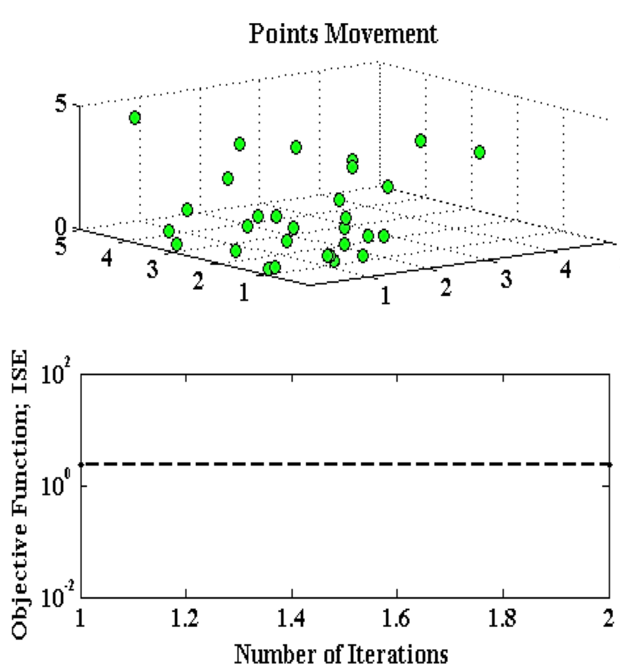

Fig. 6 Convergence of point's movement and objective function at start

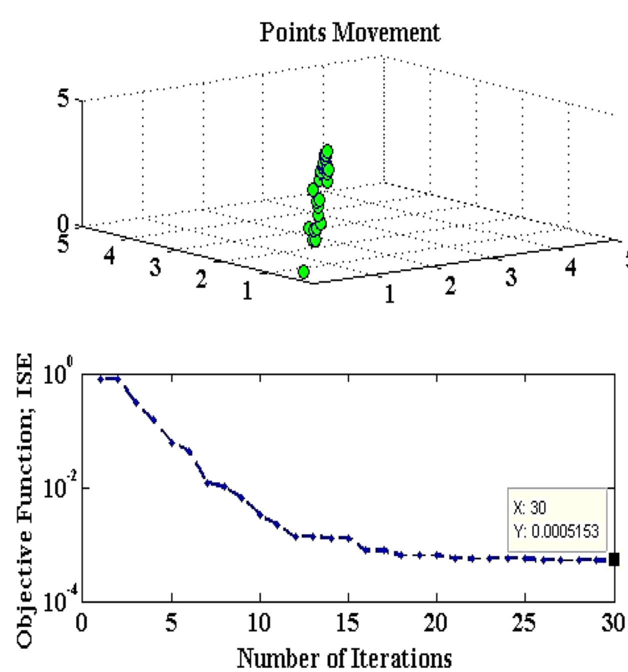

Fig. 7 Convergence of point's movement and objective function at end

Table 3 Performance analysis of HOS and LOS for Example 1

Algorithm	Original/reduced models	ISE	IAE	IRE	Rise time (s)	Settling time (s)	Over shoot (%)
–	Original model	–	–	0.0802	22.7	40.1	0
SFS algorithm (proposed)	$\frac{0.4753\,s + 0.4110}{4.4617\,s^2 + 4.7307s + 0.4110}$	5.15×10^{-4}	0.1058	0.0519	23	40.8	0
Singh et al. (2014)	$\frac{0.0496s + 0.168}{s^2 + 1.78\,s + 0.168}$	3.68×10^{-3}	0.2743	0.0494	22	39.4	0
Vishwakarma (2009)	$\frac{8\,s + 1}{100.805\,s^2 + 16.2254\,s + 1}$	128×10^{-3}	2.2586	0.0521	17.7	47.8	2.81

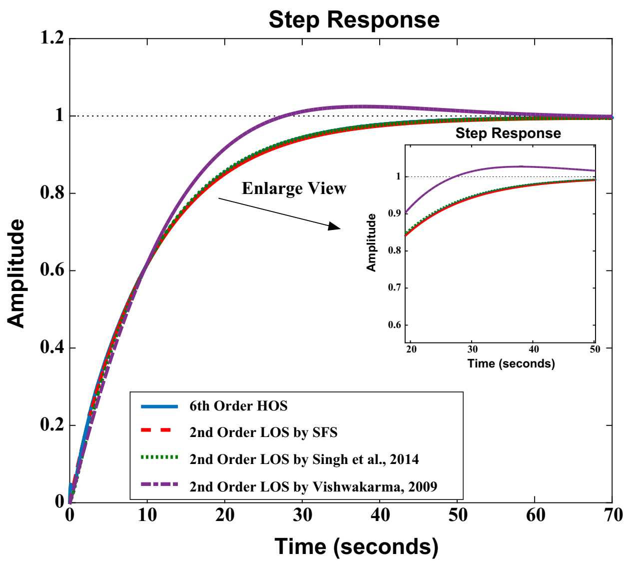

Fig. 8 Comparison of step response with existing techniques

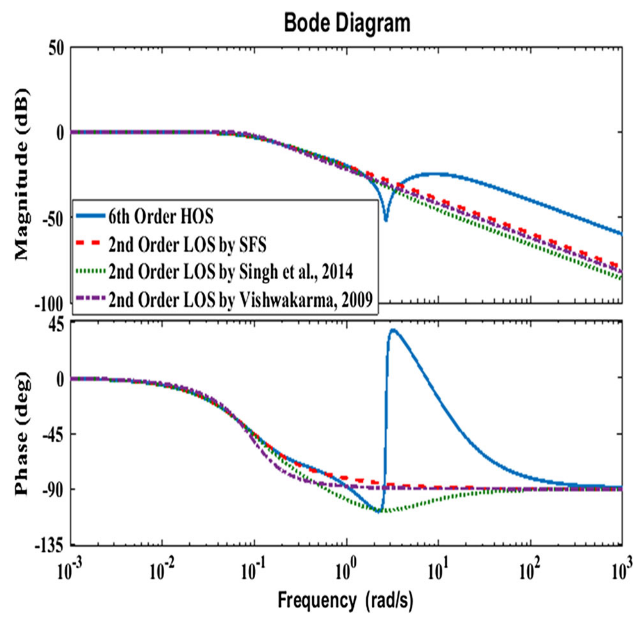

Fig. 9 Comparison of frequency response with existing techniques

Also, the SFS based LOS gives low values of performance indices; ISE and IAE in comparison to existing techniques and the value of IRE is closer to that of original HOS.

6 Implementation of SFS/PID approach in control of DC motor

The SFS has been applied to the system as per the scheme shown in Fig. 4 and the obtained parameters of PID controller are given by:

$$K_P = 1.6315; \quad K_I = 0.2798; \quad K_D = 0.2395 \tag{24}$$

Therefore, the PID controller is given by:

$$G_C = 1.6315 + \frac{0.2798}{s} + 0.2395\,s \tag{25}$$

For obtaining the above parameters of PID controller, the convergences of objective function by SFS at starting and ending is shown in Figs. 14 and 15. Now, by multiplying the transfer functions of both PID controller and DC motor, the open loop forward path transfer function is given by:

$$G_F = PID\ Controller\,(G_C) \times DC\ Motor\,(G_M) \tag{26}$$

Therefore,

$$G_F = \frac{3.5925\,s^2 + 24.4725\,s + 4.197}{1.08\,s^3 + 6.1\,s^2 + 1.63\,s} \tag{27}$$

The closed loop transfer function of DC motor with PID and unity feedback can be obtained from:

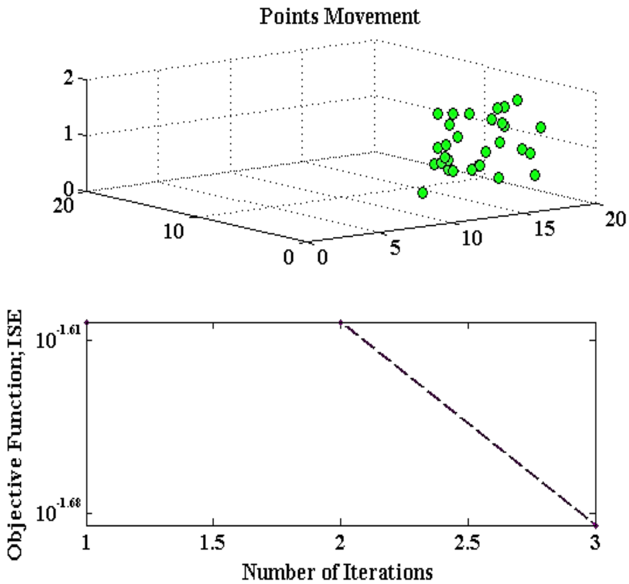

Fig. 10 Convergence of point's movement and objective function at start

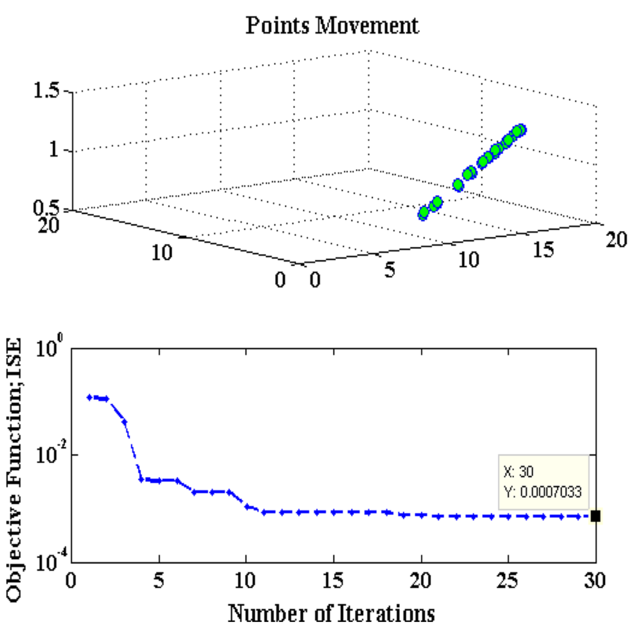

Fig. 11 Convergence of point's movement and objective function at end

$$G_{CL} = \frac{G_F}{1 + H(s)\ G_F} \tag{28}$$

where, H(s) = 1.

Graphically, the comparison of DC motor without and with PID controller tuned by SFS with ITAE as an

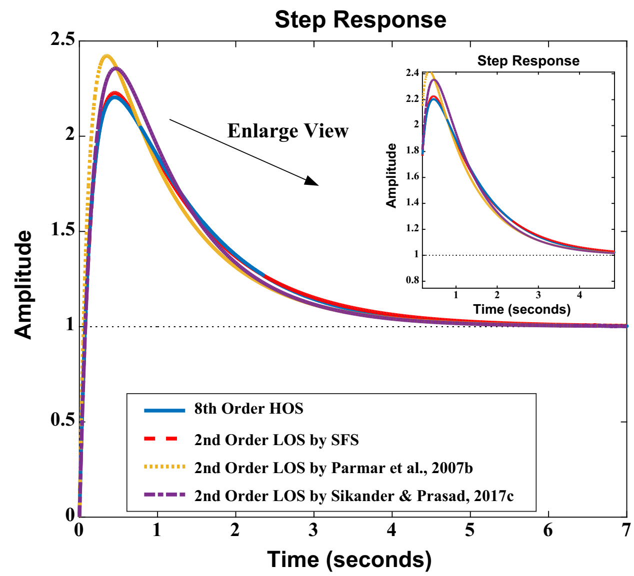

Fig. 12 Comparison of step response with existing techniques

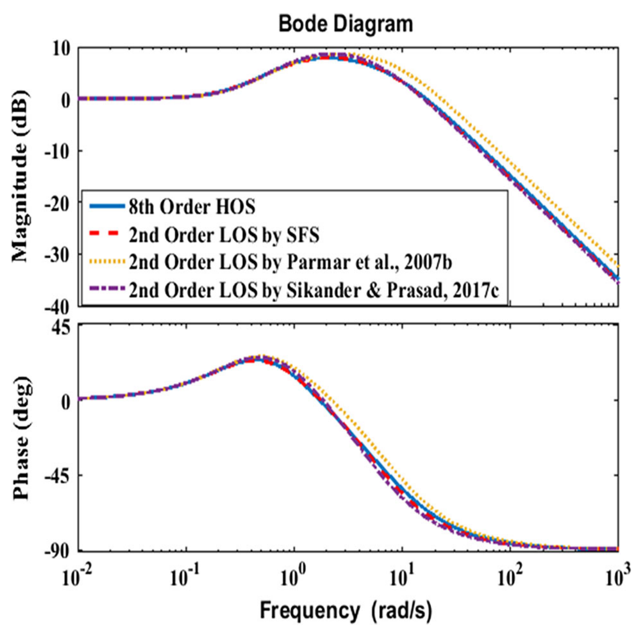

Fig. 13 Comparison of frequency response with existing techniques

objective function is shown in Fig. 16. It can be seen in Fig. 16 that, the speed of DC motor approaches to set point immediately without any overshoot with the PID controller tuned by SFS. The parameters of PID controller obtained by SFS along with other existing approaches have also been given in Table 5. Also, in Fig. 17, comparison of speed of DC motor with other existing approaches has also

Table 4 Performance analysis of HOS and LOS for Example 2

Algorithm	Original/reduced models	ISE	IAE	IRE	Rise time (s)	Settling time (s)	Over shoot (%)
–	Original model	–	–	24.2499	0.0569	4.82	120
SFS algorithm (proposed)	$\frac{16.14315\,s + 5.03619}{0.95698\,s^2 + 6.55351\,s + 5.03619}$	7.033×10^{-4}	0.0507	24.3356	0.0597	5.07	123
Mittal et al. (2004)	$\frac{7.0908s + 1.9906}{s^2 + 3s + 2}$	6.9159	0.7962	9.7906	0.142	5.47	107
Mukherjee et al. (2005)	$\frac{11.3909s + 4.4357}{s^2 + 4.2122s + 4.4357}$	2.1629	0.4503	18.1060	0.0856	3.35	129
Parmar et al. (2007a)	$\frac{24.1144\,s + 8}{s^2 + 9\,s + 8}$	1.7924	0.2990	37.5680	0.0409	4.39	142
Parmar et al. (2007b)	$\frac{24.11429\,s + 8}{s^2 + 9\,s + 8}$	4.8090×10^{-2}	0.3028	37.6872	0.0409	4.39	142
Sambariya and Arvind (2016)	$\frac{185760\,s + 40320}{118124s^2 + 109584s + 40320}$	2.3940	2.8982	1.6033	0.6862	8.7170	56.6
Sambariya and Sharma (2016a)	$\frac{1.990\,s + 0.432}{s^2 + 1.174s + 0.432}$	1.9310	2.5279	1.3856	0.5514	8.732	57.2
Sikander and Prasad (2015a)	$\frac{16.97\,s + 5.262}{s^2 + 6.893\,s + 5.262}$	6.967×10^{-4}	0.0526	24.4644	0.0594	3.1667	122.78
Sikander and Prasad (2017a)	$\frac{16.504\,s + 5.462}{s^2 + 6.197\,s + 5.462}$	1.390×10^{-2}	0.1978	25.7367	0.0598	4.36	136
Sikander and Prasad (2017b)	$\frac{22.51\,s + 8.151}{s^2 + 9\,s + 8}$	3.63×10^{-2}	0.2986	32.9381	0.0457	4.4002	123.56
Sikander and Thakur (2017)	$\frac{16.39\,s + 4.865}{s^2 + 6.627\,s + 4.865}$	3.1776×10^{-3}	0.1251	23.7287	0.0614	5.31	124

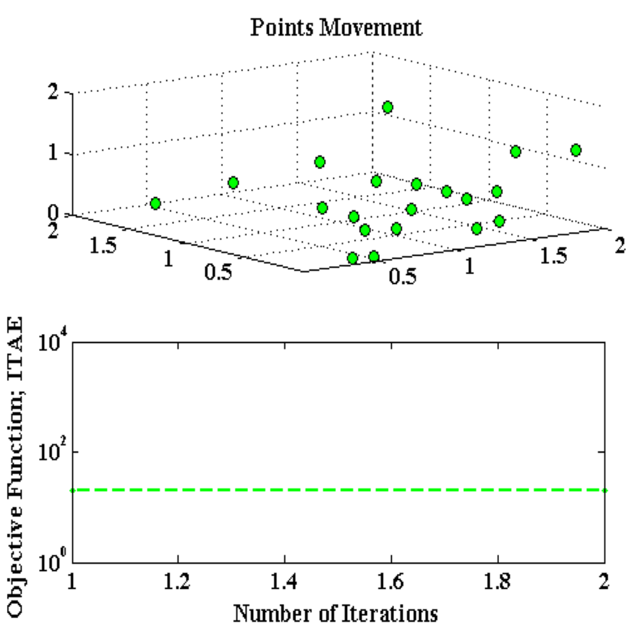

Fig. 14 Convergence of point's movement and objective function at start

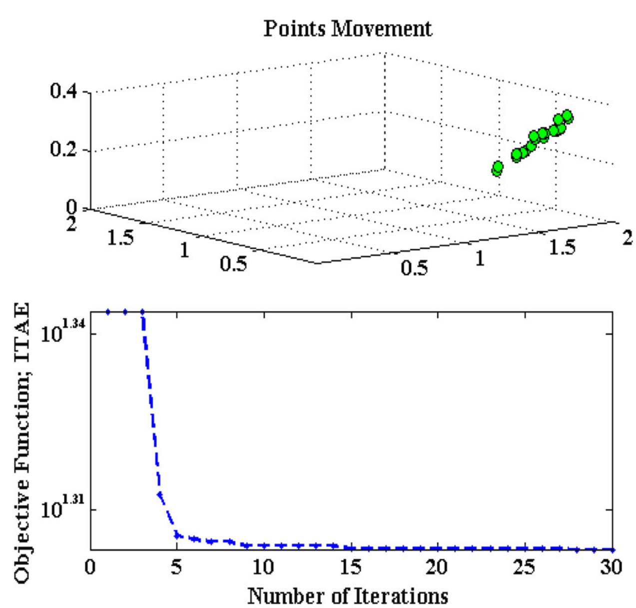

Fig. 15 Convergence of point's movement and objective function at end

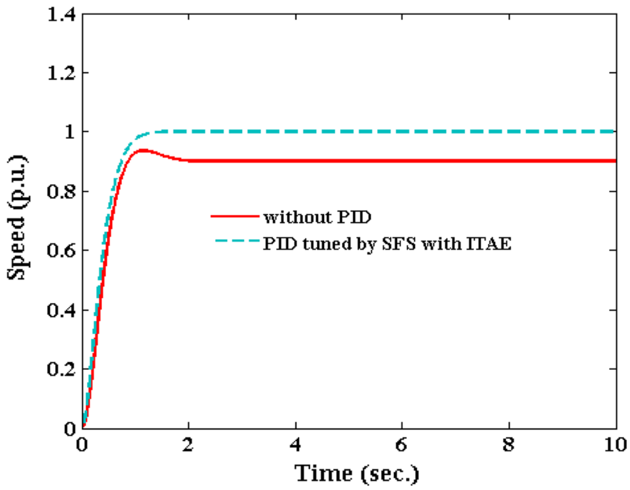

Fig. 16 Speed comparison of DC motor without and with PID controller

Table 5 Parameters of PID controller obtained by SFS, IWO & PSO

Algorithm	K_P	K_I	K_D
SFS (proposed)	1.6315	0.2798	0.2395
IWO (Khalilpuor et al. 2011)	1.5782	0.4372	0.0481
PSO (Khalilpuor et al. 2011)	1.5234	1.3801	0.0159

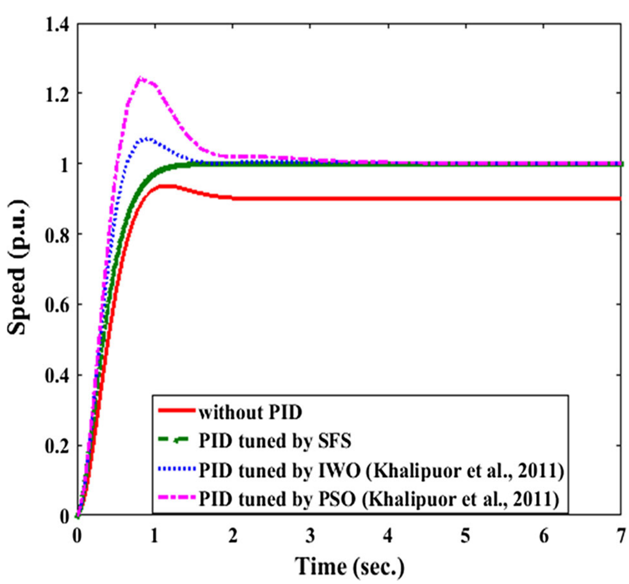

Fig. 17 Speed comparison of DC motor with existing techniques

been shown. It can be seen in Fig. 17 that, SFS/PID approach with ITAE gives no overshoot in comparison to existing techniques.

Therefore,

$$G_{CL}(SFS) = \frac{3.5925\,s^2 + 24.4725\,s + 4.197}{1.08\,s^3 + 9.6925\,s^2 + 26.1025\,s + 4.197} \tag{29}$$

Further, the transient response's parameters for the closed loop responses are also given in Table 6 which shows that the proposed SFS/PID approach gives no overshoot when compared with other existing approaches.

7 Conclusions

The present work deals with application of SFS algorithm in approximation and control of LTI systems. In system's approximation, the SFS has been used to minimize the ISE in between the transient responses of HOS and LOS in order to get all the unknown parameters of LOS. The systems available in the literature have been taken as test/simulation examples. The step and frequency responses of HOS and LOS have been compared with each other along with the recently published methods in the literature. Also, in simulation examples, comparisons of ISE, IAE and IRE have been shown with existing methods to show the effectiveness of SFS algorithm. The obtained ISE and IAE values by SFS algorithm are very low and the IRE value of SFS based LOS is very close to HOS when compared with existing methods. The transient response's parameters of HOS and LOS by SFS and other existing techniques have also been compared.

The application of SFS algorithm in control of LTI system has also been shown in which standard DC motor is used as test system. The ITAE has been taken as an objective/fitness function. Comparison of proposed SFS/PID approach has also been shown with other existing techniques; such as IWO/PID and PSO/PID. The simulation results reveal that SFS/PID scheme with ITAE as an objective function gives no overshoot and other parameters such as; settling and rise times are also comparable with existing techniques.

Table 6 Comparison of transient response's parameters

Algorithm	Over shoot (%)	Settling time (s)	Rise time (s)
SFS (proposed)	0	1.06	0.638
IWO (Khalilpuor et al. 2011)	7.16	1.95	0.493
PSO (Khalilpuor et al. 2011)	25.5	2.38	0.409

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