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Design of Robust PID Controller Using Hybrid Algorithm for Reduced Order Interval System

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ABSTRACT

A system with parameter variation within bound creates interval in coefficients in the system polynomial and hence it is called as interval system. In this study, a model order reduction for linear interval system is attempted. A convergence technique is attempted to reduce the numerator polynomial. The denominator polynomial is reduced by using the methods such as retention of Markov parameter and time moments technique. A numerical approach is proposed to compute the reduced order interval model for a higher order linear time variant model. Also in this study, a novel technique using Particle Swarm assisted Bacterial Foraging Optimization (PSO-BFO) based hybrid algorithm is proposed to search the PID controller parameters such as K_p, K_i and K_d. The algorithm is to obtain the best possible PID parameters with Integral Squared Error (ISE) criterion minimization is as the objective function. Initially the controller parameters are obtained for reduced order model; then it is tested with the higher order model. A simulation is carried out to shows that the effectiveness of proposed model reduction algorithm and the controller performance. From the result it is observed that, the projected method provides enhanced performance for the interval system.

Key words: Interval system, Kharitonov polynomial, model order reduction, bacterial foraging optimization, particle swarm optimization

INTRODUCTION

In Industries and academics, model based analysis are widely proposed to study the transient and steady state behaviour of the physical systems such as machineries, process loops, etc. Most of the modeling methods proposed in the literature may provide only the approximated models around the operating region of the process under study. The conventional modeling methods may fail to provide the approximated model when the system has parametric perturbation. Since, in this study, we proposed an interval system analysis accounting the possible perturbations. A variety of modeling methods (Dolgin and Zeheb, 2004) has been discussed to construct an approximated lower order model for the real time systems.

Model based analysis is used to study the behaviour of the physical system. Many attempts have been made to model the physical system with parametric uncertainties as interval system (Dolgin and Zeheb, 2004). When the real time system is modeled, its order is too large. Hence, analysis like steady state and transient response is very difficult. So the model reduction is very much essential for the analysis and control of physical system. Some of the model reduction techniques have been proposed by various researchers for interval system (Younseok, 2007). Model order reduction of interval system without sacrificing the response of higher order model is a challenging task. But the validity of the method is based on the resulting error obtained by the model reduction (Babu and Pappa, 2008).

Identification of fault is an important task in intelligent control system, since a fault can lead to reduction in performance even breakdown. Fault detection identifies the deviation of set point in the monitored system. Ideal system and the model behave exactly the same, but in real time system fault is detected when the behaviour of the system differs from reference beyond the tolerance level.

The method presented by Lepschy and Viaro (1983), is a mixed method using differentiation and Pade's reduction techniques which avoids the use of gain factor. In Lucas model reduction technique (Lucas, 1988, 1992) for an Interval system is based on differentiation technique for both the numerator and denominator. The method has a serious limitation, since it has the formation of two Routh arrays for the numerator and denominator, it also always retains only one time moment of the original system which affects the time response of the system. This method has a one more serious limitation; it cannot be implemented for systems having a difference of more than one in the order of denominator and numerator polynomials.

In this study, a convergence technique is attempted to reduce denominator polynomial and the numerator polynomial is reduced using biased model reduction which helps to retain the first (k-1) time moments and Markov parameter of the original system (Hsu *et al.*, 2007). Using Kharitonov polynomial, reduced order model is converted into 16 set of polynomials of transfer function model that describes the system behaviour with in bound.

In recent years, nature inspired algorithms, such as Particle Swarm Optimization (PSO) and Bacterial Foraging Algorithm (BFO) methods are widely proposed to find solutions for highly complex engineering optimization problems.

PSO is proposed by Kennedy and Eberhart (1995), it is a swarm based optimization technique inspired by the flock of birds and school of fish. The basic and the modified form of this algorithm was widely proposed by the researchers to find the best possible solutions for their problems. BFO is also one of the nature inspired algorithm which mimics the foraging methods of *E. coli* bacterium. This algorithm was widely proposed for parameter optimization. Rajinikanth and Latha (2011) proposed the BFO algorithm to optimize the PID controller parameter for a class of unstable system. With a comparative study they concluded that even though it provides the best optimized value, its speed of convergence is slower than the PSO algorithm.

The Integral Squared Error (ISE) criterion is used to guide the Bacterial Foraging based Particle Swarm Optimization (BF-PSO) algorithm to search the controller parameters such as K_p, K_i and K_d. It is used to find a set of controller parameters are obtained for each Kharitonov polynomial. A hull set for each controller parameter is calculated from the 16 set of controller parameters which are obtained for 16 Kharitonov polynomial using Model Interval Analysis (MIA). Controller performance is analyzed by computing ISE and compared with Bandyopadhyay *et al.* (1997) method. Using the generalized Kharitonov theorem and Kharitonov rectangle, stability of original and reduced order interval model is verified.

In control literature, recently soft computing approach based PID tuning methods are widely proposed by the researchers for a class of stable and unstable system models. Ali and Majhi (2006) and Rajinikanth and Latha (2011) discussed PSO based PID tuning technique for stable and unstable system. Korani *et al*. (2009), proposed a hybrid PSO-BFO algorithm to optimize the controller parameter for stable systems and compared the performance with the PSO and BFO based methods. Since, in this study, PSO-BFO based hybrid optimization algorithms is attempted. In this method, the PSO algorithm is used to speed up the process of BFO in order to achieve faster convergence with best optimized parameter.

INTERVAL SYSTEM ANALYSIS

Recent trend in the area of system modeling is to model the system with uncertainties. Presence of uncertainties in the system components, process input, disturbances, measurement noise, leakage in joints, system model will vary frequently. One way to model the system with uncertainty is interval system. In interval system the parameter variations within bounds creates intervals in the coefficients of the system polynomial. i.e., a model which has the parameter with interval coefficients like s^2+[5,6]s+[0.23,0.34]. Each coefficient will have a lower and upper limit. Interval analysis is done based on the interval arithmetic equation (1-4). Stability of Interval system can be analyzed using Kharitonov stability criterion and Kharitonov rectangle (Tan and Atherton, 2000).

Interval arithmetic: A real interval x is a nonempty set of real members:

$$x = [\underline{x}, \bar{x}] = \{x \in R: \underline{x} \le x \le \bar{x}\}$$

where, $\underline{x}$ is called the infimum and $\bar{x}$ is called the supremum. The set of all intervals over R is denoted by IR. Let x, y be two real interval numbers. The arithmetic operations like addition, subtraction, multiplication and division can be performed with the following equations:

- **Addition:** $x+y = [\underline{x} + \underline{y}, \bar{x}+\bar{y}]$ (1)
- **Subtraction:** $x-y = [\underline{x} + \bar{y}, \bar{x}+\underline{y}]$ (2)
- **Multiplication:** $x \times y = [\min\{\underline{x}y + \underline{x}\bar{y}, \bar{x}\bar{y}, \bar{y}\bar{x}\}, \max\{\underline{x}y, \underline{x}\bar{y}, \bar{x}\underline{y}, \bar{y}\bar{x}\}]$ (3)
- **Division:**

$$\frac{x}{y} = \begin{cases} [\bar{x}/\underline{y}, \infty] & \text{if } \bar{x} \le 0 \text{ and } \bar{y} = 0, \\ [-\infty \bar{x}/\underline{y}] U [\bar{x}/\underline{y}, \infty] & \text{if } \bar{x} \le 0 \text{ and } \underline{y} < 0 < \bar{y}, \\ [-\infty \bar{x}/\bar{y}] & \text{if } \bar{x} \le 0 \text{ and } \underline{y} = 0, \\ [-\infty, \infty] & \text{if } \underline{x} < 0\bar{x}, \\ [-\infty \underline{x}/\underline{y}] & \text{if } \bar{x} \le 0 \text{ and } \bar{y} = 0, \\ [-\infty \underline{x}/\underline{y}] U [\underline{x}/\underline{y}, \infty] & \text{if } \underline{x} \ge 0 \text{ and } \underline{y} < 0 < \bar{y}, \\ [\underline{x}/\underline{y}, \infty] & \text{if } \underline{x} \ge 0 \text{ and } \underline{y} = 0, \end{cases} \tag{4}$$

GENERALIZED KHARITONOV THEOREM

Consider the numerator polynomial of the open loop system is:

$$GP(s) = [\underline{b}_{n-1}, \bar{b}_{n-1}]S^{n-1} + [\underline{b}_{n-2}, \bar{b}_{n-2}]S^{n-2} + \ldots + [\underline{b}_1, \bar{b}_1]S + [\underline{b}_0, \bar{b}_0] \tag{5}$$

The numerator polynomial N(s) is split into two components g(s) and h(s), Where:

g(s) = Polynomial of even degree
h(s) = Polynomial of odd degree

Defining the two even polynomials:

$$\begin{aligned} G_1(S) &= \underline{b}_0 + \vec{b}_2 s^2 + \underline{b}_4 s^4 + \cdots \\ G_2(S) &= \underline{b}_0 + \vec{b}_2 s^2 + \underline{b}_4 s^4 + \cdots \end{aligned} \tag{6}$$

Defining the two odd polynomials:

$$\begin{aligned} h_1(S) &= \underline{b}_1 s + \vec{b}_3 s^3 + \underline{b}_5 s^5 + \cdots \\ h_2(S) &= \vec{b}_1 s + \vec{b}_3 s^3 + \vec{b}_5 S^5 + \cdots \end{aligned} \tag{7}$$

Then Kharitonov Polynomials can be formulated by Eq. 8:

$$\begin{aligned} K_{11}\,N(S) &= g_1(s) + h_1(s) \\ K_{12}\,N(S) &= g_1(s) + h_2(s) \\ K_{21}\,N(S) &= g_2(s) + h_1(s) \\ K_{22}\,N(S) &= g_2(s) + h_2(s) \end{aligned} \tag{8}$$

The Kharitonov polynomials [$K_{11}N(s)$, $K_{12}N(s)$, $K_{21}N(s)$, $K_{22}N(s)$] and [$K_{11}D(s)$, $K_{12}D(s)$, $K_{21}D(s)$, $K_{22}D(s)$] are obtained using Eq. 6-8 for the numerator and denominator, respectively. Kharitonov theorem states that, the robust stability of the family of the closed-loop interval polynomials is guaranteed if and only if all Kharitonov polynomials of the system are stable. Obviously, consists of 32 segment polynomials which are generally referred to as generalized Kharitonov segment polynomials. It follows that the entire family of the closed-loop polynomials D(s,p,q,a,b) is Hurwitz stable if and only if the 32 generalized Kharitonov segment polynomials DE(s, l) are all Hurwitz stable.

HYBRID OPTIMIZATION ALGORITHM

Particle swarm optimization (PSO) algorithm: Particle Swarm Optimization (PSO) (Kennedy and Eberhart, 1995; Ren and Zhong, 2011) algorithm is a swarm intelligence technique, attempts to mimic the natural way of group communication of individual knowledge. It is a population based search algorithm where each individual is referred to as particle. In this method, a population of swarm is initialized with random positions S_i and velocities V_i. At the beginning, each particle of the population is scattered randomly throughout the entire search space and with the guidance of the performance criterion, the flying particles dynamically adjust their velocities according to their own flying experience and their companions flying experience. Each particle remembers its best position obtained so far which is denoted pbest and the overall best out of all the particles in the population is called gbest:

$$v_i(t+1) = w^t v_i(t) + C_1 * r_1(\text{pbest} - S_i(t)) + C_2 * r_2(\text{gbest} - S_i(y)) \tag{9}$$

$$W^t = (W_{max} - Iter)x\left[\frac{W_{max} - W_{min}}{Iter_{max}}\right] \quad (10)$$

Bacterial foraging optimization (BFO) algorithm: In the process of foraging behaviour of *E. coli* bacteria undergo four stages, namely, chemotaxis, swarming, reproduction and elimination and dispersal (Passino, 2002). In search space, BFO (Supriyono and Tokhi, 2011) seek optimum value through the chemotaxis of bacteria and realize quorum sensing via assemble function between bacterial and satisfy the evolution rule of the survival of the fittest make use of reproduction operation and use elimination-dispersal mechanism to avoiding falling into premature convergence.

Chemotaxis: The motion patterns that the bacteria will generate in the presence of chemical attractants and repellents are called chemotaxis. For *E. coli*, this process was simulated by two different moving ways: run or tumble.

Swarming: An interesting group behavior has been observed for several motile species of bacteria including *E. coli* and *S. typhimurium*. When a group of *E. coli* cells is placed in the center of a semisolid agar with a single nutrient chemo-effector, they move out from the center in a traveling ring of cells by moving up the nutrient gradient created by consumption of the nutrient by the group.

Reproduction: According to the rules of evolution, individual will reproduce themselves in appropriate conditions in a certain way. For bacterial, a reproduction step takes place after all chemotactic steps.

Elimination-dispersal: In the evolutionary process, elimination and dispersal events can occur such that bacteria in a region are killed or a group is dispersed into a new part of the environment due to some influence. They have the effect of possibly destroying chemotactic progress, but they also have the effect of assisting in chemotaxis, since dispersal may place bacteria near good food sources (Fig. 1).

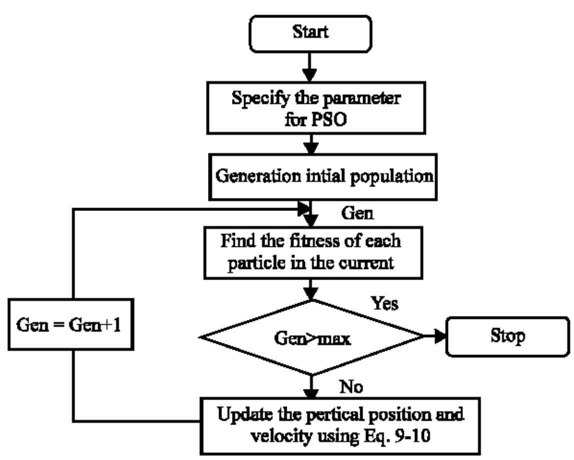

Fig. 1: Flowchart of PSO for tuning of controller parameter

CONTROLLER TUNING

The following flowchart explains the controller tuning method using PSO.

Proposed algorithm is used to find the controller parameter such as K_p, K_i and K_d for all the 16 set of Kharitonov polynomials of the reduced order model. BF-PSO algorithm is performed with the following parameter Size of the swarm is 10, Dimension of the problem is 3 and $c_1 = 0.12$; $c_2 = 1.2$ and momentum of inertia (w = 0.9). PID controller is designed for all the set of Kharitonov polynomials. Finally hull set of controller parameter is identified as interval controller gain.

PROPOSED METHOD FOR MODEL REDUCTION:

A typical nth order interval system is represented by its transfer function:

$$G_n(S) = \frac{(\underline{B}_{n-1}, \overline{B}_{n-1})S^{n-1} + (\underline{B}_{n-2}, \overline{B}_{n-2})S^{n-2} + \cdots (\underline{B}_1, \overline{B}_1)S + (\underline{B}_0, \overline{B}_0)}{(\underline{A}_n, \overline{A}_n)S^n + (\underline{A}_{n-1}, \overline{A}_{n-1})S^{n-1} + \cdots (\underline{A}_1, \overline{A}_1)S + (\underline{A}_0, \overline{A}_0)} \quad (11)$$

Then the reduced (kth) order model:

$$G_k(S) = \frac{(\underline{b}_{k-1}, \overline{b}_{k-1})S^{k-1} + (\underline{b}_{k-2}, \overline{b}_{k-2})S^{k-2} + \cdots (\underline{b}_1, \overline{b}_1)S + (\underline{b}_0, \overline{b}_0)}{(\underline{a}_k, \overline{a}_k)S^n + (\underline{a}_{k-1}, \overline{a}_{k-1})S^{k-1} + \cdots (\underline{a}_1, \overline{a}_1)S + (\underline{a}_0, \overline{a}_0)}$$

$$G_k(S) = \frac{N_k(S)}{D_k(S)} \quad (12)$$

Reduced order denominator: Where $(\underline{B}_i, \overline{B}_i)$ is a denominator polynomial coefficient, having interval structure. The kth order reduced model denominator polynomials $D_k(s)$ where (k = 1,2,3....n-1) are obtained by the new algorithms suggested in this study. This method is based on the truncation technique.

- For k = 1:

$$D_1(s) = (\underline{A}_0, \overline{A}_0) + \frac{(n-1)C_{n-1}}{n-1}(\underline{A}_1, \overline{A}_1) \quad (13)$$

- For k = 2:

$$D_2(s) = (\underline{A}_0, \overline{A}_0) + \frac{(n-1)C_{n-2}}{n-1}(\underline{A}_1, \overline{A}_1)s + \frac{(n-2)C_{n-2}}{nc_{n-2}}(\underline{A}_1, \overline{A}_1)s^2 \quad (14)$$

General representation of the kth order denominator is:

$$D_k(s) = \sum_{i-1}^{k+1}(\underline{A}_{i-1}, \overline{A}_{i-1}) \frac{(n-1+1)\,C_{n-k}}{nC_{n-k}} s^{i-1} \text{ where, } k = 1, 2, 3, \ldots \quad (15)$$

Reduced order numerator: The numerator of reduced order $N_k(s)$ polynomial can be obtained by the following method:

$$N_k(s) = N_{kt}(s) + N_{km}(s)$$

where, N_{kt} (s) is Numerator term from time constants, N_{km} (s) is Numerator term from Markov parameter, k = t+m:

$$= T_1 + T_2 s + \ldots + T_t s^{k-m+1} + M_m s^{k-m} \ldots + M_2 s^{k-2} + M_1 s^{k-1} \quad (16)$$

In general:

$$T_t(s) = (\underline{a}_0, \overline{a}_0)\frac{(\underline{B}_{t-1}, \overline{B}_{t-1})}{(\underline{A}_0, \overline{A}_0)} \quad (17)$$

$$[\underline{M}_i, \overline{M}_i] = \frac{1}{(\underline{A}n, \overline{A}n)}\sum_{j=0}^{m}(\underline{B}_{(n-1)}, \overline{B}_{(n-1)})\ (\underline{a}_{(k-(m-i))}, \overline{a}_{(k-(m-i))}) - \sum_{j=0}^{m-1}(\underline{M}j, \overline{M}j)\ [\underline{A}_{(n-(m-i))}, \overline{A}_{(n-(m-i))}] \quad (18)$$

With Markov parameter $(\underline{M}_0, \overline{M}_0] = (0, 0)$.

ILLUSTRATIONS

Let the seventh order interval system obtained from the literature:

$$G(s) = \frac{[1.9,\ 2.1]S^6 + [24.7,\ 27.3]S^5 + [157.7,\ 174.3]S^4 + [541.9,\ 599.02]S^3 + [929.9,\ 1027.8]S^2 + [721.81,\ 797.79]S + [187.055,\ 206.745]}{[.95,\ 1.05]S^7 + [8.779,\ 9.703]S^6 + [52.2,\ 57.8]S^5 + [182.8,\ 202.1]S^4 + [429.02,\ 474.1]S^3 + [572.4,\ 632.7]S^2 + [325.2,\ 359.5]S + [57.35,\ 63.389]} \quad (19)$$

A second order model is obtained using the suggested method, retaining initial time moment and one Markov parameter of the given system i.e., k = 2, m = 1, t = 1.

The second order model denominator can be obtained using Eq. 14:

$$= [27.26,\ 30.13]s^2 + [92.937,\ 102.72]s + [57.352,\ 63.789] \quad (20)$$

The numerator N2(s) to retain initial Markov parameter and time moment is obtained using Eq. 17 and 18:

$$(\underline{T}_1, \overline{T}_1 = (169.24,\ 229.64) \quad (21)$$

Markov parameter can be calculated by:

$$[M_1, M_1] = \frac{1}{[\underline{A}_4, \overline{A}_4]}(\underline{B}_3, \overline{B}_3)\ (\underline{a}_{3-(1-1)}, \overline{a}_{3-(1-1)}) - 0*(\underline{A}_3, \overline{A}_3) \quad (22)$$

$$(M_1, M_1) = [49.32,\ 66.6]$$

Hence, the reduced 2nd order numerator can be obtained using Eq. 21 and 22:

$$N_2(S) = [49.32,66.6]S+[169.24,229.64] \quad (23)$$

Hence, the 2nd order reduced order system using Eq. 20 and 23:

$$G_2(S) = \frac{[49.32, 66.6]s + [169.24, 229.64]}{[27.26,30.13]s^2 + [92.937,102.72]s + [57.352, 63.789]} \quad (24)$$

Kharitonov polynomials of numerator polynomial of Eq. 19 are:

$$\begin{aligned}
K_{n1} &= 1.9s^6+24.7s^5+174.3s^4+599.02s^3+929.96s^2+721.81s+206.75 \\
K_{n1} &= 1.9s^6+24.7s^5+174.3s^4+599.02s^3+929.96s^2+721.81s+206.75 \\
K_{n2} &= 2.1s^6+27.3s^5+157.7s^4+541.98s^3+1027.8s^2+797.79s+187.06 \\
K_{n3} &= 2.1s^6+24.7s^5+157.7s^4+599.02s^3+1027.8s^2+721.81s+187.06 \\
K_{n4} &= 1.9s^6+27.3s^5+174.3s^4+541.98s^3+929.96s^2+797.79s+206.75
\end{aligned} \quad (25)$$

Kharitonov polynomials of denominator polynomial of Eq. 19 are:

$$\begin{aligned}
K_{d1} &= 0.95s^7+8.779s^6+57.8s^5+202.1s^4+429.02s^3+572.4s^2+359.5s+63.389 \\
K_{d2} &= 1.05s^7+9.703s^6+52.2s^5+182.8s^4+474.1s^3+632.7s^2+325.2s+57.35 \\
K_{d3} &= 1.05s^7+8.779s^6+52.2s^5+202.1s^4+474.1s^3+572.4s^2+325.2s+63.389 \\
K_{d4} &= 0.95s^7+9.703s^6+57.28s^5+182.8s^4+429.02s^3+632.7s^2+359.5s+57.35
\end{aligned} \quad (26)$$

Using Eq. 25-26 Kharitonov rectangle was drawn and analysis the stability of higher order model.

The characteristic equation of the closed loop system with unity feedback is Eq. 27.

$$\begin{aligned}
1+GH(s) &= [.95, 1.05]S^7 + [10.967, 11.8]S^6 + [76.9, 85.1]S^5 + [340.5, 376.4]S^4 \\
&+ [970.92,1073.12]S^3 + [1502.3,1660.5]\, S^2 + [1046.9,1157.29]S + [244.4, 270.1]
\end{aligned} \quad (27)$$

Characteristic equation of Second order reduced model is:

$$1+G_rH(s) = [27.26,30.13]s^2+[4.72,6.21]s+[7.52,10.764] \quad (28)$$

Using interval analysis reduced order model is modified as:

$$1+G_rH(s) = [1,1]s^2+[4.72,6.21]s+[7.52,10.764] \quad (29)$$

RESULTS AND DISCUSSION

In this study, a higher order model is obtained from the literature (Tomar *et al.*, 2009), a seventh order stable model is reduced into second order stable model by using convergence technique. Stability of both higher order model and reduced order model can be analyzed using Kharitonov rectangle. In general Kharitonov rectangle is obtained between edge polynomial verses frequency. Figure 2a-c represents the Kharitonov rectangle of stable higher order model. It passes through seven quadrants; hence order of the system is seven. Also it encircles the origin in anticlockwise direction without passing through the origin, so the system is stable system.

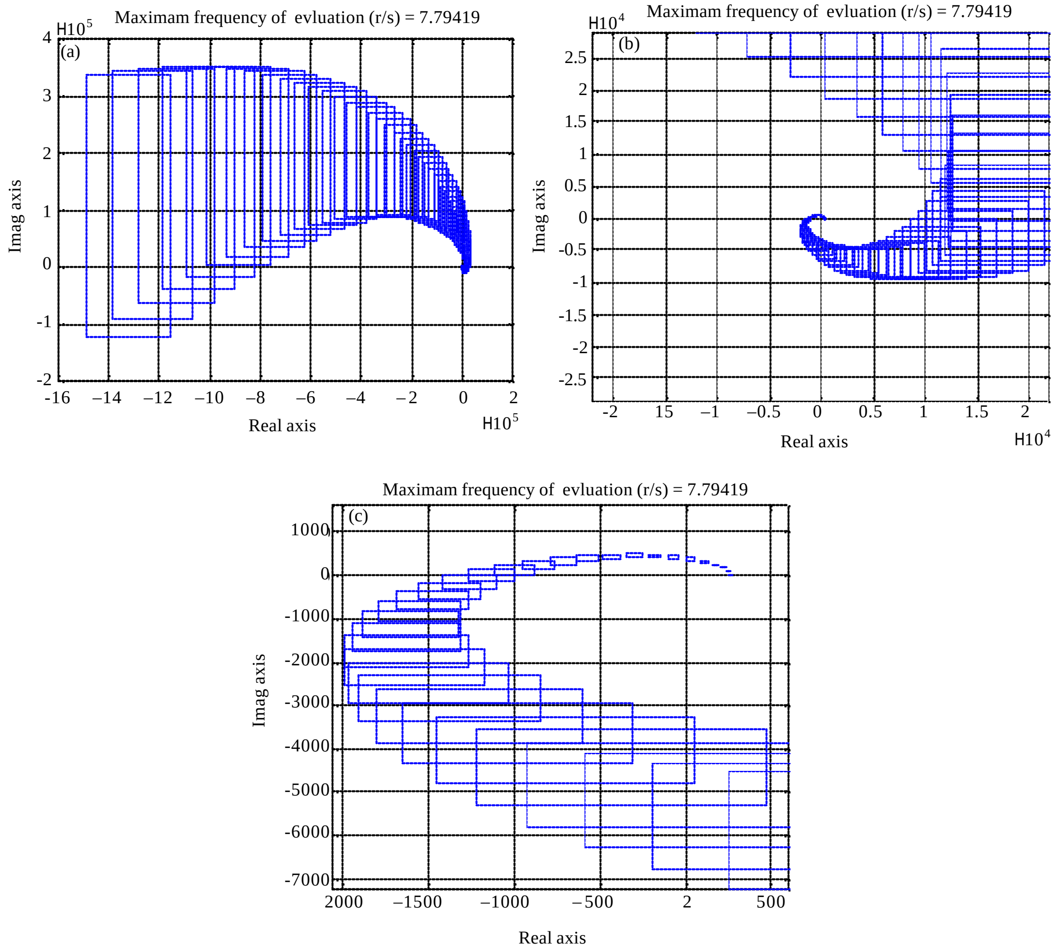

Fig. 2(a-c): (a) Kharitonov rectangle for higher order system, (b) Enlarged view of (a) and (c) More enlarged view of (a)

Figure 3 shows the Kharitonov rectangle of stable reduced order model. It has been drawn between the real axis and imaginary axis of Kharitonov edge polynomials obtained for various frequencies. Figure 3 passes two quadrants (first and second) without passing through origin, hence the reduced order model is also stable and order of the model is 2.

It passes through two quadrants and encircles the origin with anticlockwise direction. Anticlockwise encirclement of origin shows stability of the system. To study the steady state and transient state behaviour of the system, step response and impulse response has been obtained for both higher and reduced order model. Figure 4 shows the Step response of the Kharitonov polynomial of the higher and reduced order models. Among Four responses curve, two is drawn for higher order model, remaining two is for reduced order model. Reduced order responses are within higher order response.

To study the system with sudden disturbance, impulse response is used. Figure 5 shows the impulse response of the Kharitonov polynomial of the higher and reduced order models. Similar to step response analysis, impulse response has been obtained for both higher and reduced order model. Here also reduced order model response curve are within the higher order model response curve.

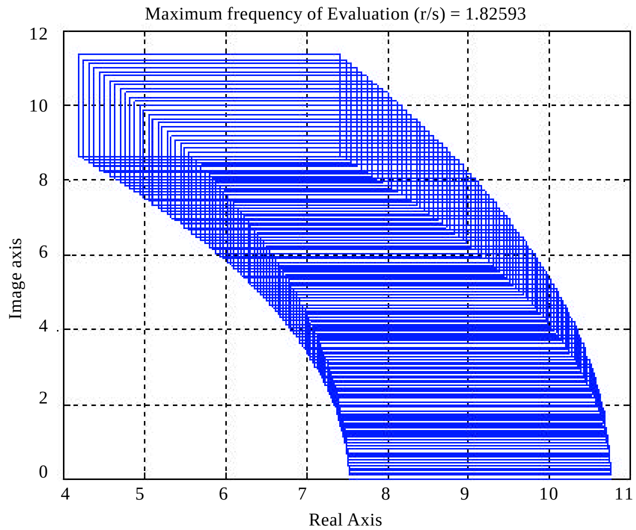

Fig. 3: Kharitonov rectangle for reduced order model

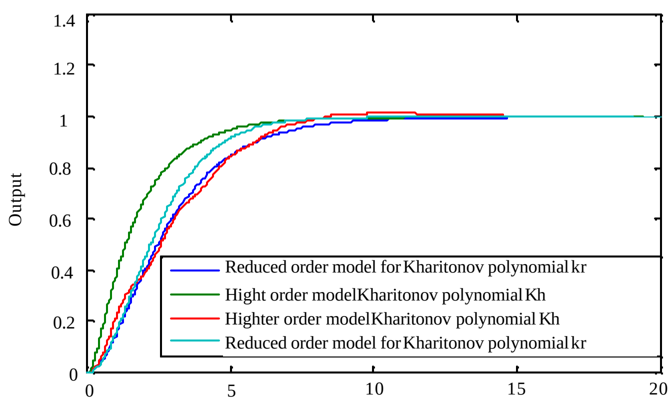

Fig. 4: Comparison of step response of higher order and reduced order model

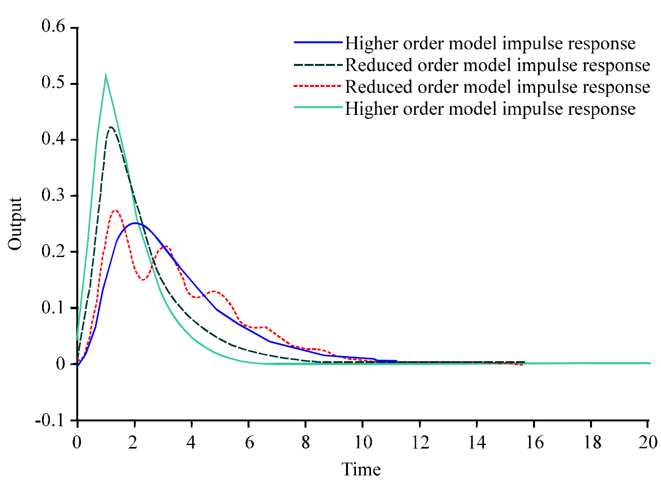

Fig. 5: Comparison of impulse response of higher order and reduced order model

Table 1: Comparison of error analysis for various model order reduction

Method of order reduction	Reduced model	ISE for higher order model	ISE for lower order model
Proposed method	$\frac{[49.32, 66.6]s + [169.24, 229.64]}{[27.26,30.13]s^2 + [92.937,10272]s + [57.352, 63.789]}$	0.808	0.8215
Devender Kumar Saini method	$\frac{[634.7, 429.7]s + [271.7, 293.2]}{[61.5, 68.99]s^2 + [255.7,347.1]s + [83.3,87.67]}$	0.062	4.927
B. Bandyopadhyay	$\frac{[1.16,1.84]s + [0.27, 0.53]}{s^2 + [0.52, 0.83]s + [0.08.3, 0.16]}$	2.259	5.954

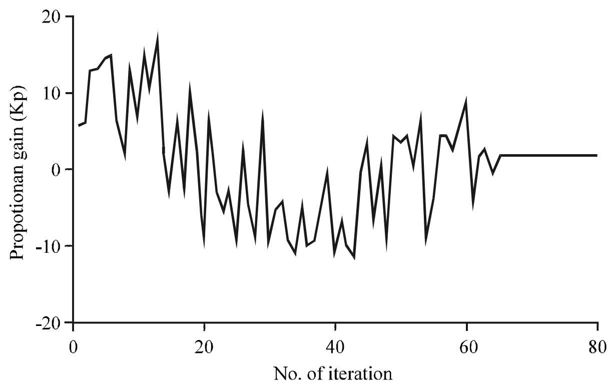

Fig. 6: Convergence chart for controller setting (K_p)

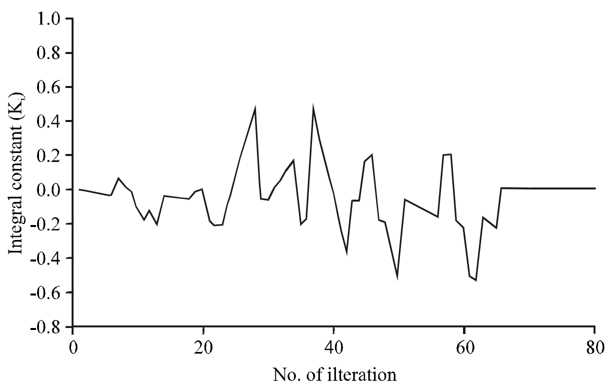

Fig. 7: Convergence chart r setting (K_i)

Table 1 shows that the proposed method reduces the higher order model effectively with less error compare to other methods. Compared with Bandyopadhyay and Devender Kumar Saini method, the integral squared error of the proposed method is very low.

Controller Settings for the reduced order model are obtained using BF-PSO. Figure 6 is convergence chart for proportional controller parameter. It is observed that the proportional constant (K_p) is converged with 1.758 for the Kharitonov polynomial K $_{r1}$ The optimization algorithm searches the proportional constant in wide span, after 66th iteration it has converged to the constant value.

From the Fig. 7, it is observed that the integral constant (K_i) is converged to 0.009 for the Kharitonov polynomial K_{11}. The optimization algorithm searches the proportional constant in wide span, after 66th iteration it has converged to the constant value.

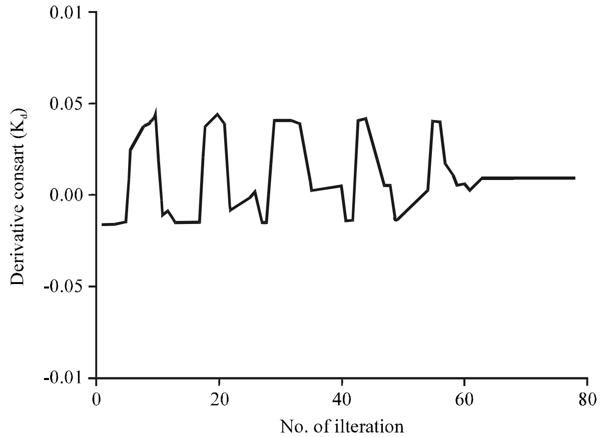

Fig. 8: Convergence chart for controller setting (K_d)

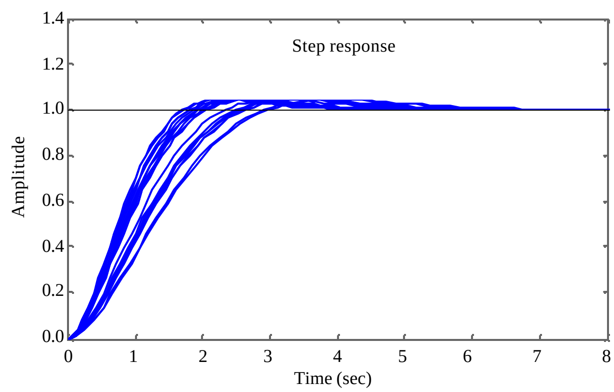

Fig. 9: Step response higher and lower order model with controller

From the Fig. 8, it is observed that the derivative controller Constant (K_d) is converged with K_d=0.049 for the Kharitonov polynomial K_{11}. The optimization algorithm searches the proportional constant in wide span, after 66th iteration it has converged to the constant value.

$$K_p = [1.34912, 1.758] \text{ and } K_i = [0.0184, 0.12528] \text{ and } K_d = [0.0126, 0.5821]$$

Figure 6-8 shows convergence flow of the controller setting. Figure 9 gives the comparison of the step response of higher and reduced order closed loop model. $K_i = 0.0629$, $K_d = 0.0049$ for K_{11} and similarly controller parameter is calculated for all other set of Kharitonov polynomials K_{12}, K_{13} etc. From the set of controller parameter identified for all 16 Kharitonov polynomials, Controller parameter in interval form can be computed by using the hull set.

CONCLUSION

The proposed method simplifies the mathematical complexities. This model reduction method is based on convergence technique, generates stable reduced order model for original higher order stable model by retaining both initial time moments and Markov parameters. Reduced order model performance match the higher order model performance for both steady state and transient state of the time response. A controller parameter is identified for the reduced order model, using bacterial foraging based Particle swarm optimization (PSO) which control the higher order model effectively. Step and impulse responses are obtained are compared. But the time taken by the algorithm is large compared to other methods.

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