

Order Reduction based on Coulomb's and Franklin's laws Algorithm

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Ram Kumar · Afzal Sikander

Abstract The Coulomb and Franklin laws (CFL) algorithm is used to construct a lower order model of higher-order continuous time linear time-invariant (LTI) systems in this study. CFL is quite easy to implement in obtaining reduced order model of large scale system in control engineering problem as it employs the combined effect of Coulomb's and Franklin's laws to find the best values in search space. The unknown coefficients are obtained using the CFLA methodology, which minimises the integral square error (ISE) between the original and proposed ROMs. To achieve the reduced order model, five practical systems of different orders are considered. Finally, multiple performance indicators such as the ISE, integral of absolute error (IAE), and integral of time multiplied by absolute error were calculated to determine the efficacy of the proposed methodology. The simulation results were compared to previously published well-known research.

Keywords CFL Algorithm · Model Order Reduction · Optimization · Control System

1 Introduction

The majority of control system designs are complex from a research standpoint. A lower order system that is a replica of the original higher order system is used to make the analysis simpler. Reduced order modelling is the method of obtaining a simplified structure from a high-order system. As a result, this reduced-order model helps to evaluate the behaviour of original higher-order models and making design and analysis work simpler. In recent years, several studies have looked at the model order reduction in detail. Recently, Afzal Sikander [1] developed a modified cuckoo search algorithm for obtaining the lower order model of the original higher order system. Ghosh and Senroy [2] developed a balanced truncation method for MOR and Sikander and Prasad [3] proposed a basic time domain MOR technique based on improved Hermite normal form. Desai and Prasad [4] have developed a new reduced order method for LTI structures based on Routh approximation (RA). Erol and Eksin [5] developed Big Bang–Big Crunch (BB-BC) optimization for MOR in 2006.

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In this reduced method the denominator polynomial is calculated using Routh Approximation to maintain stability and the reduced order of numerator is evaluated with the BB-BC algorithm. Different literature that discussed about the reduced order modelling are given in [6–9]. In the world of new era of machine engineering, the optimization approach is not recent. Different researchers working the field of model order reduction have taken different cost function, such as minimising the integral square of impulse response error [10], minimising integral error [11], minimising weighted time integral error [12], or minimising L1 and L2 norm [13] for finding the reduced model using optimization techniques. Nature-inspired optimization methods have been commonly employed to identify the reduced order model of higher order systems. One of most common bio - inspired optimization techniques are the genetic algorithm (GA) created by Goldberg [14] and particle swarm optimization (PSO) created by Kennedy and Eberhart [15]. In addition, researchers in the different literature's proposed a variety of mixed approaches for reduced order modelling. In these mixed processes, the idea is to retain the reduced system's stability. Stability of the reduced model is often obtained by the techniques that use the stability-preserving methods to minimise the denominator polynomial [8, 16, 17]. Afzal Sikander [18] suggested a mixed method in which the stability equation approach was used to determine the reduced model's stable denominator, and then PSO was utilised to determine the reduced order of numerator. As a result, new techniques for lower order modelling are in high demand these days since they reduce hardware complexity, machine costs, and compile time. So, based on the Coulomb's and Franklin's law, this paper proposed a novel technique for order reduction in continuous time LTI systems [19]. For an original higher order stable system, the suggested technique produces a stable lower order system. The proposed optimization approach is used to achieve a stable reduced system by using the ISE value as an objective function.

2 Problem Description

Continuous time linear time invariant system of the higher order is considered as:

$$G_k(s) = \frac{N_{k-1}(s)}{D_k(s)} = \frac{\sum_{i=0}^{k-1} a_i s^i}{\sum_{i=0}^k b_i s^i} \quad (1)$$

where a_i and b_i are the coefficients of numerator and denominator polynomial of the original higher order models respectively, $a_0 = b_0$, If steady state value is unity. The objective of model order reduction is to produce the lower order system of the order ' r ' ($r < d$) such that it retain all important features of the original large scale system. Reduced order system can be expressed as:

$$G_r(s) = \frac{N_{r-1}(s)}{D_r(s)} = \frac{\sum_{i=0}^{r-1} c_i s^i}{\sum_{i=0}^r d_i s^i} \quad (2)$$

where c_i and d_i are the coefficients of lower order model's numerator and denominator respectively.

3 Proposed Methodology based on CFLA

Coulomb's and Franklin's laws Algorithm (CFLA) is a meta-heuristic algorithm which was first implemented in [19]. This algorithm is based on the Coulomb's and Franklin's law

theories. The CFLA uses the two different principles for getting the optimized results, which are given below.

First Law: This law used principle of attraction and repulsion phenomena of electrons and known as Coulomb's Law. This phenomena determines the interaction between two separate point charges that are placed at some distances.

Second Law: According to this law every object is having equal numbers of positive and negative charges. This law was given by the Franklin and known as Franklin's Law.

CFLA uses different populations of point charges named X that roam around the different areas in search space. Using the random generator, global optimal solution for different populations are generated in search space to form the initial populations. CFLA mathematical model is a four-phase mechanism that are following:

- Initialization phase
- Attraction / repulsion phase
- Probabilistic ionization phase
- Probabilistic contact phase

3.1 Initialization Phase

m is the point having dimension D . O is object formed by point charges, X is the populations of point charges and X_{ij} is the each individuals generated. Then formation of object O , population of point charges X is as follows:

$$\begin{aligned} O &= [O_1, O_2, \dots, O_n] \\ X &= [X_1, X_2, \dots, X_m] \\ X_{ij} &= [x_{i1}, x_{i2}, \dots, x_{iD}] \end{aligned}$$

The starting populations of point charges generated are as follows:

$$x_{ij} = U \left(x_j^{\min}, x_j^{\max} \right) \quad (3)$$

where, i varies from $(1, 2, \dots, m)$ and j is in the range of $(1, 2, \dots, D)$. U is a random vector generated evenly between the range x_j^{\min} and x_j^{\max} . Then, it is converted into several objects ($O_1 \dots \dots O_n$) by distributing the initial populations.

3.2 Attraction / Repulsion Phase

According to the Coulomb's law of attraction, the point charges are displaced due the effects of attraction and repulsion between charges. Cost function value (F_i) is calculated using the net force that acts on the point charge (X_i). Objective of the CFLA is to reduce the net force (cost function value) acting on point charges. Best location of each object is updated iterative by following relations

$$\begin{aligned} x_j^{new} &= x_{ij}^{old} + \left| \cos \theta_j^{new} \right|^2 \times \left(x_j^{best} - x_j^{Worst} \right) + \\ &\left| \sin \theta_j^{new} \right|^2 \times \left(\text{mean} \left(\sum_{n=1}^{a_{max}} x_{jn} \right) - \text{mean} \left(\sum_{n=1}^{r_{max}} x_{jn} \right) \right) \end{aligned} \quad (4)$$

where, $\theta_j^{initial} = U(0, 2\pi)$

$$\theta_j^{new} = \theta_j^{old} + U\left(0, \frac{3}{2}\pi\right)$$

The values of a_{\max} and r_{\max} are obtained using the relations given below:

$$a_{\max} = a_0 \times (1 + \cos \theta) \quad (5)$$

$$r_{\max} = r_0 \times (1 - \cos \theta) \quad (6)$$

3.3 Probabilistic Ionization Phase

Location of the point charges x_j may be displaced by the ionization energy. It is mathematically modelled by the following relations.

$$x_j^{new} = x_j^{Best} + x_j^{Worst} - x_j^{old} \text{ if } \text{rand}(i) \leq p_i \quad (7)$$

j is the control variable and chosen as

$$j = \text{round}(\text{unifrnd}(1, D)) \quad (8)$$

where, $\text{rand}(i)$ is random number in the range of $[0, 1]$ for point charges.

3.4 Probabilistic Contact Phase

In this phase best and worst objective values are passed to its neighbour point charges. point. Mathematically, Probabilistic contact phase can be modelled as follows:

$$\begin{aligned} x_j^{BestObj_1} &= x_j^{BestObj_n}, \dots, x_j^{BestObj_n} = x_j^{BestObj_{n-1}} \\ x_j^{WorstObj_1} &= x_j^{WorstObj_n}, \dots, x_j^{WorstObj_n} = x_j^{WorstObj_{n-1}} \end{aligned} \quad (9)$$

where, x_j^{Best} and x_j^{Worst} are the best and worst objective values respectively. The working flowchart of CFLA are shown in Figure 1. Following performance indices are considered to find the performance indices and analyzing the performance of proposed CFLA method of obtaining reduced order model.

$$ISE = \int_0^{\infty} [f_1(t) - f_2(t)]^2 dt \quad (10)$$

$$ITSE = \int_0^{\infty} t [f_1(t) - f_2(t)]^2 dt \quad (11)$$

$$IAE = \int_0^{\infty} |f_1(t) - f_2(t)| dt \quad (12)$$

$$ITAE = \int_0^{\infty} t |f_1(t) - f_2(t)| dt \quad (13)$$

ISE, ITSE, IAE, and ITAE, respectively, are integral square error, time multiplied by integral square error, integral absolute error and time multiplied by integral absolute error. Difference between step response of $f_1(t)$ and $f_2(t)$ is considered as the error for calculating the performance indices.

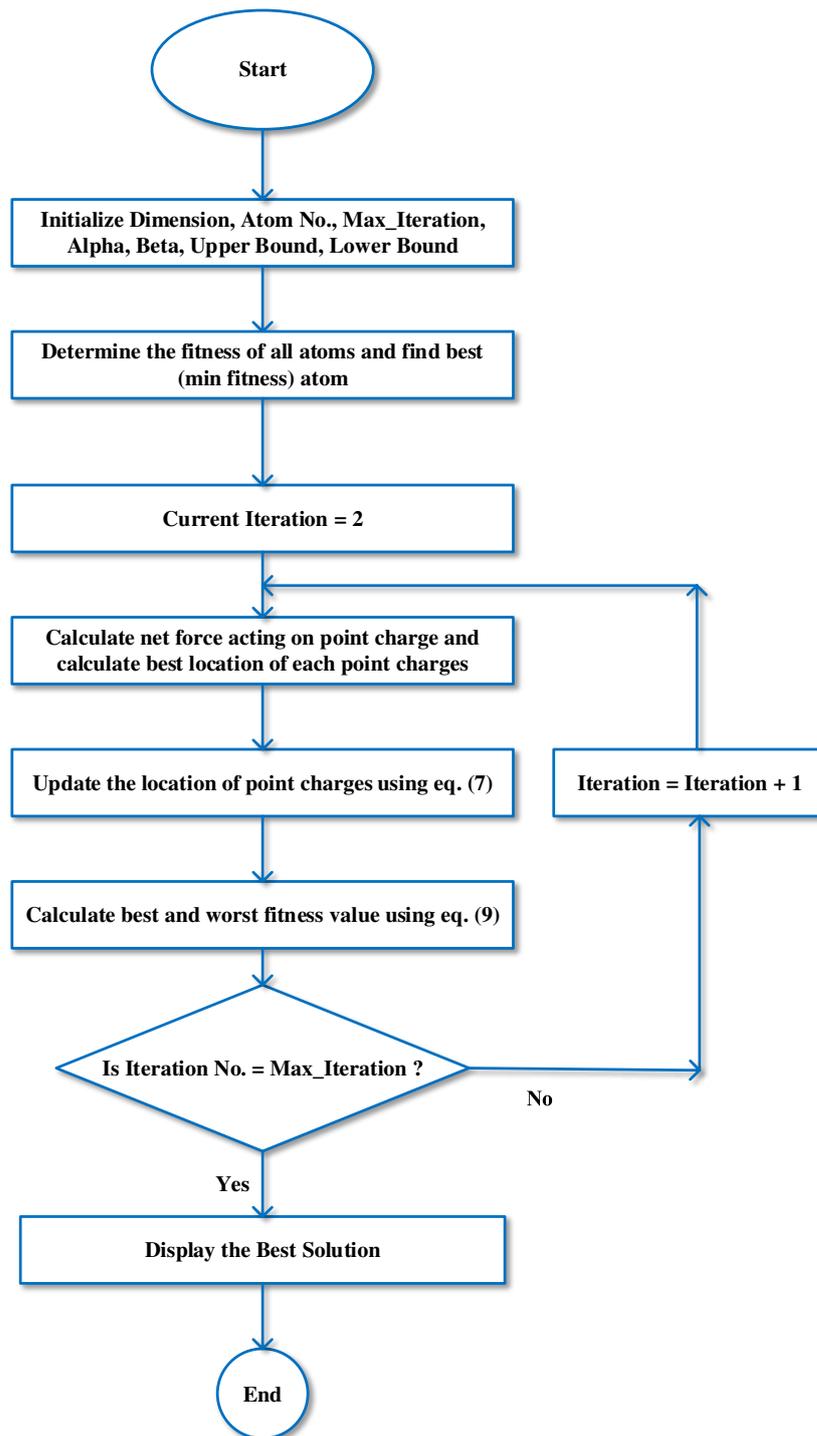


Fig. 1: CFLA Flow Chart

4 Simulation Results

In this section various types of simulation analysis like step response, frequency response of five different examples of different orders taken from the recent literature [1] are presented.

Example 1. In this example a 4th order stable system is considered from [1] for finding its reduced order system.

$$G_4(s) = \frac{s^3 + 7s^2 + 24s + 24}{s^4 + 10s^3 + 35s^2 + 50s + 24}$$

Second order reduced system by proposed technique (CFLA) given in section 3 is

$$R_2(s) = \frac{2.4830s + 2.3223}{2.9969s^2 + 5s + 2.3223}$$

Reduced system obtained using Modified Cuckoo Search [1] in 2018 is as follows

$$R_2(s) = \frac{0.77s + 1.649}{s^2 + 2.548s + 1.649}$$

Reduced system obtained using RA and BB-BC [4] in 2013 is as follows

$$R_2(s) = \frac{0.8058s + 0.7944}{s^2 + 1.65s + 0.7944}$$

Reduced system obtained by Genetic Algorithm (GA) [20] in 2011 is as follows

$$R_2(s) = \frac{0.4s + 1}{0.5s^2 + 1.5s + 1}$$

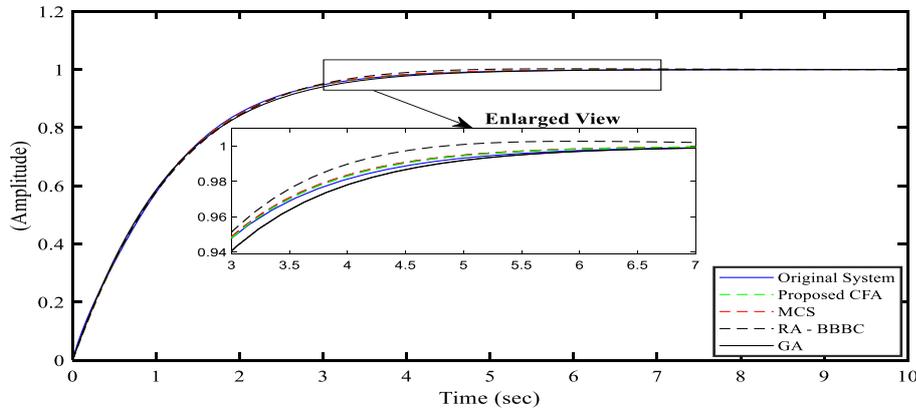


Fig. 2: Step response for Example 1.

Different responses obtained for proposed reduced model and original system is shown in Figures 2 and 3. Step response of reduced order system obtained by proposed CFLA method is tested with different recently published work and shown in Fig. 2. From the step response plotted in Fig. 2. It is obvious that the suggested CFLA method's reduced order

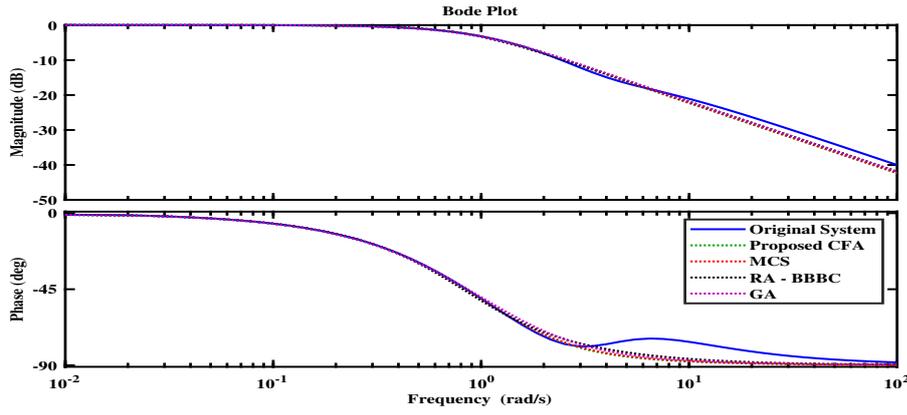


Fig. 3: Bode plot for Example 1.

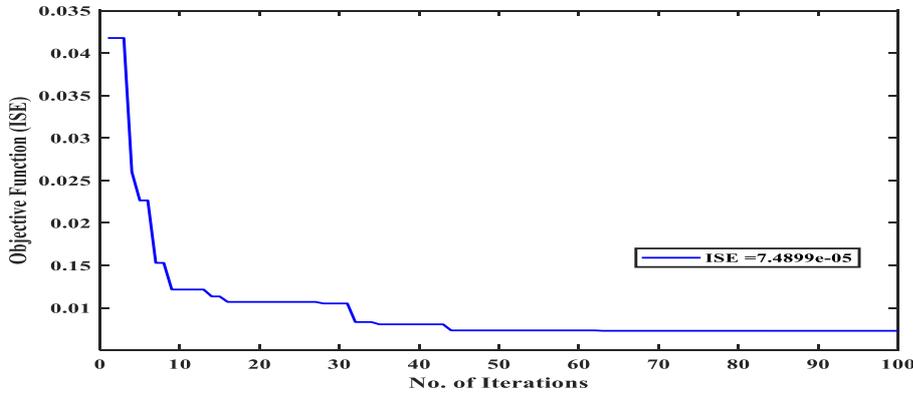


Fig. 4: Iteration Graph for Example 1.

transfer function is extremely similar to the original higher order continuous time LTI system. In Fig. 3 bode plot of the original system and reduced system obtained by proposed CFLA method is compared with [1, 4, 20]. Table 1 compares the parameters of original system and reduced system obtained by proposed CFLA method and recent publications given in [1, 4, 20]. Table 1 shows that the ISE value obtained using the proposed CFLA method is 7.4899×10^{-5} which is less than the reduced order system achieved using the MCS algorithm [1]. Also, the different parameters like settling time, peak value and different performance indices like ITAE, IAE, ITSE is calculated to show the efficacy of the proposed CFLA method.

Example 2. An eighth order system is considered from [1] whose transfer function is given below

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

Second order reduced system by proposed technique (CFLA) given in section 3 is

$$R_2(s) = \frac{16.8825s + 5.2446}{s^2 + 6.8559s + 5.2446}$$

Table 1: Comparative analysis of original and reduced system for Example 1.

Methods	Peak Overshoot	Settling Time	ISE	ITSE	IAE	ITAE
Original System	1.0000	3.9269	—	—	—	—
Proposed Method	1.0000	3.8510	7.4899×10^{-05}	7.0220×10^{-05}	0.0159	0.0367
MCS [1]	1.0000	3.8287	7.6986×10^{-05}	8.3151×10^{-05}	0.0168	0.0410
RA and BB-BC [4]	1.0027	3.6292	2.8472×10^{-04}	0.0010	0.0444	0.1738
GA [20]	0.9999	4.0898	2.3891×10^{-04}	4.3814×10^{-04}	0.0316	0.0709
FDA and ESA [16]	0.9999	4.0177	2.643×10^{-04}	4.9814×10^{-04}	0.0261	0.3966

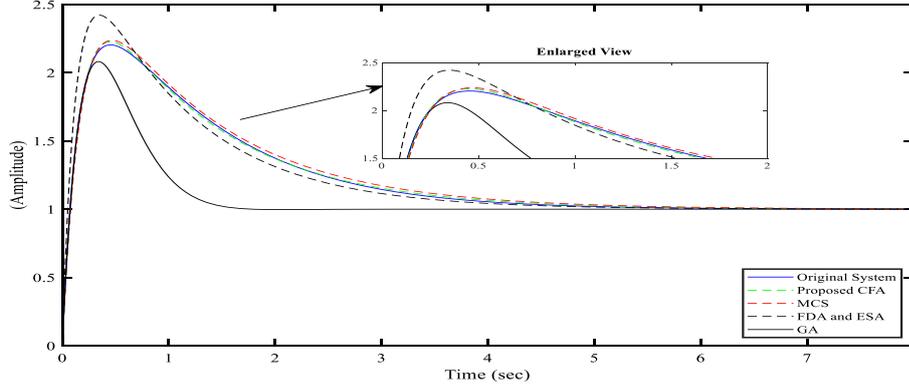


Fig. 5: Step response for Example 2.

Reduced system obtained using Modified Cuckoo Search [1] in 2018 is as follows

$$R_2(s) = \frac{16.39s + 4.865}{s^2 + 6.627s + 4.865}$$

Reduced system obtained by Genetic Algorithm (GA) [20] in 2011 is as follows

$$R_2(s) = \frac{16.9686s + 15.2295}{s^2 + 6.8996s + 15.2295}$$

Reduced system obtained using RA and BB-BC [4] in 2013 is as follows

$$R_2(s) = \frac{24.11429s + 8}{s^2 + 9s + 8}$$

Different responses obtained for proposed reduced model and original system is shown in Figures 5 and 6. Step response obtained by proposed CFLA method is compared with different recently published work and shown in Fig. 5. The reduced order transfer function derived by the proposed CFLA approach is extremely near to the original higher order continuous time LTI system, as shown by the step response given in Fig. 5. In Fig. 5 bode plot of the higher order system and reduced order system obtained by proposed CFLA method is compared with [1, 4, 20, 21]. Table 2 is showing the comparative analysis of obtained lower order system along with original system and recent published article given in [1, 4, 20, 21]. The ISE value obtained using the proposed CFLA method is 6.9504×10^{-4} which is very

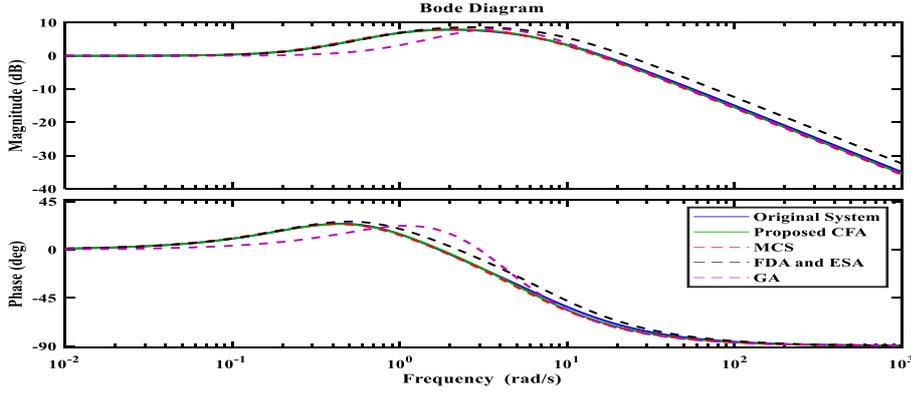


Fig. 6: Bode plot for Example 2.

Table 2: Performance comparison of original and reduced system for Example 2.

Methods	Peak Overshoot	Settling Time	ISE	ITSE	IAE	ITAE
Original System	2.2036	4.7796	—	—	—	—
Proposed Method	2.2276	5.0077	6.9504×10^{-04}	0.0012	0.0585	0.1611
MCS [1]	2.2373	5.1906	0.0033	0.0069	0.1357	0.3661
FDA and ESA [22]	2.4212	4.3678	0.0481	0.0236	0.3006	0.3869
ESA and PA [16]	2.4212	4.3678	1.7924	1.9824	0.3006	0.3869
GA [20]	2.0813	1.5036	0.5290	0.7403	1.2276	2.1804

much lower than the reduced order system obtained by MCS algorithm [1]. Also, the different parameters like settling time, peak value and different performance indices like ITAE, IAE, ITSE is compared to demonstrate the performance of the suggested CFLA approach.

Example 3. To demonstrate the effectiveness of the proposed method an approximate model of the thermal diffusion system is considered in this example, which is of 10^{th} order and represented as follows.

$$G_{10}(s) = \frac{540.70748 \times 10^{17}}{\prod_{i=1}^{10} (s + \lambda_i)}$$

where

$$\lambda_1 = 2.04, \quad \lambda_2 = 18.3, \quad \lambda_3 = 50.13, \quad \lambda_4 = 95.15,$$

$$\lambda_5 = 148.85, \quad \lambda_6 = 205.16, \quad \lambda_7 = 252.21$$

$$\lambda_8 = 298.03, \quad \lambda_9 = 320.97, \quad \lambda_{10} = 404.16$$

Second order reduced system by proposed technique (CFLA) given in section 3 is

$$R_2(s) = \frac{0.0096s + 15.7980}{s^2 + 8.9268s + 15.798}$$

Reduced system obtained using Modified Cuckoo Search algorithm [1] in 2018 is as follows

$$R_2(s) = \frac{0.007842s + 16.06}{s^2 + 9.868s + 16.06}$$

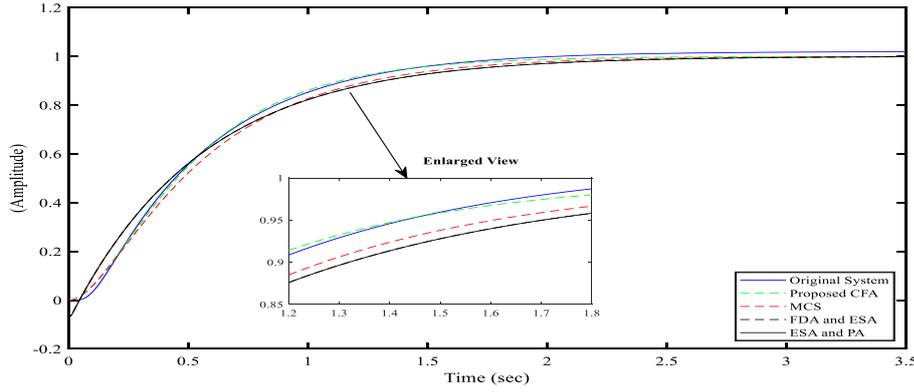


Fig. 7: Step response for Example 3.

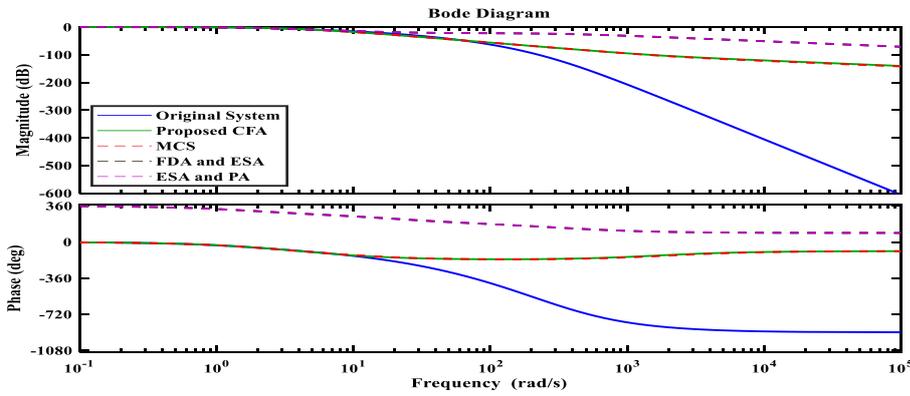


Fig. 8: Bode plot for Example 3.

Reduced system obtained by ESA and PA [16] in 2007 is as follows

$$R_2(s) = \frac{-28.367s + 647.60193}{s^2 + 359.999s + 647.60193}$$

Reduced system obtained using ESA and PA [22] in 2007 is as follows

$$R_2(s) = \frac{-28.3902s + 647.6004}{s^2 + 359.999s + 647.6004}$$

Different responses obtained for proposed reduced model and original system is shown in Figures 7 and 8. In Fig. 7, the step response of a reduced order system generated using the suggested CFLA approach is compared to that of other previously published studies. From the step response plotted in Fig. 7 it is clearly visible that reduced order transfer function obtained by proposed CFLA method is very close to the original higher order continuous time LTI system. The original system and the reduced system derived by the proposed CFLA approach and reduced system obtained by [1, 20, 21, 21] are compared in Fig. 8. Table 3 is showing the comparative analysis of original system as well as reduced system obtained

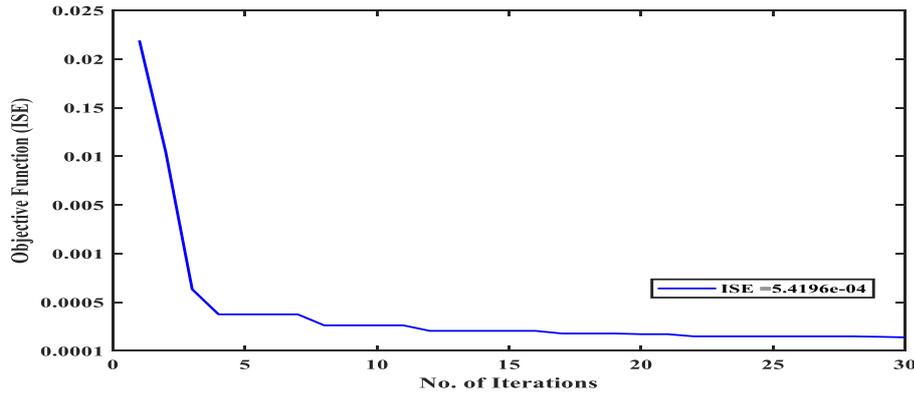


Fig. 9: Iteration Graph for Example 3.

by proposed CFLA method and recent published article given in [1, 20, 21, 21]. It is evident from the Table 3 that ISE value obtained using the proposed CFLA method is 5.4196×10^{-4} which is very much lower than the reduced order system obtained by MCS algorithm [1]. Performance criteria such as settling time, peak value, and performance indices such as ITAE, IAE, and ITSE are also calculated to demonstrate the efficacy of the proposed CFLA approach.

Table 3: Performance comparison of original and reduced system for Example 3.

Methods	Peak Overshoot	Settling Time	ISE	ITSE	IAE	ITAE
Original System	1.0187	2.0078	—	—	—	—
Proposed Method	0.9997	1.7940	5.4196×10^{-4}	0.0012	0.0377	0.0799
MCS [1]	0.9990	2.0274	0.0018	0.0028	0.0772	0.1288
FDA and ESA [22]	0.9981	2.1270	0.0031	0.0039	0.0956	0.1515
ESA and PA [16]	0.9981	2.1270	0.0031	0.0039	0.0956	0.1516
LSMR [23]	0.9981	2.0124	4.3986×10^{-4}	0.1125	0.0581	0.4600

Example 4. In this example a ninth order complex roots system is considered to obtain the 3rd order reduced system.

$$G_9(s) = \frac{s^4 + 35s^3 + 291s^2 + 1093s + 1700}{s^9 + 9s^8 + 66s^7 + 294s^6 + 1029s^5 + 2541s^4 + 4684s^3 + 5856s^2 + 4620s + 1700}$$

Third order reduced system by proposed technique (CFLA) given in section 3 is

$$R_3(s) = \frac{0.0016s^2 + 0.0039s + 1.075}{s^3 + 1.6522s^2 + 2.1952s + 1.075}$$

Reduced system obtained using Modified Cuckoo Search algorithm [1] in 2018 is as follows

$$R_3(s) = \frac{0.001935s^2 + 0.005725s + 1.073}{s^3 + 1.681s^2 + 2.183s + 1.073}$$

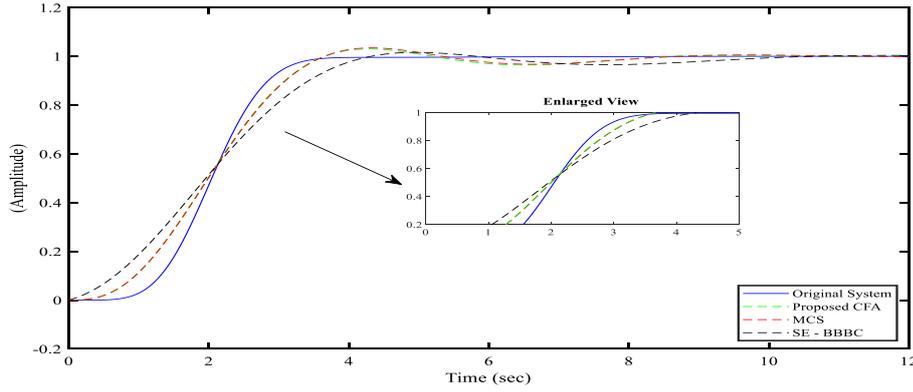


Fig. 10: Step response for Example 4.

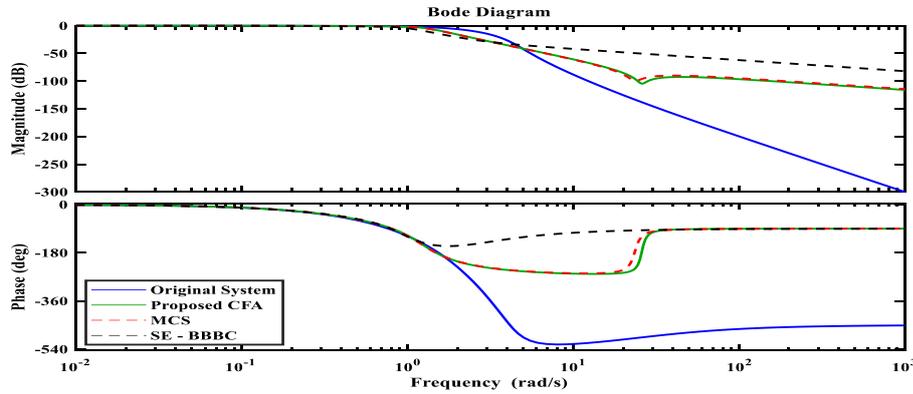


Fig. 11: Bode plot for Example 4.

Reduced system obtained by SE and BB – BC [4] in 2007 is as follows

$$R_3(s) = \frac{0.0789s^2 + 0.3142s + 0.493}{s^3 + 1.3s^2 + 1.34s + 0.493}$$

Figures 10 and 11 are showing the responses obtained for proposed reduced model and original system. Step response of reduced order system obtained by proposed CFLA method is compared with different recently published work is shown in Fig. 10. From the step response plotted in Fig. 10 it is clearly visible that reduced order transfer function obtained by proposed CFLA method is very close to the original higher order continuous time LTI system. In Fig. 11 bode plot of the original system and reduced system obtained by proposed CFLA method is compared with [1, 10, 17, 20, 21, 21]. Table 4 is showing the comparative analysis of original system as well as reduced system obtained by proposed CFLA method and recent published article given in [1, 10, 17, 20, 21, 21]. ISE value obtained using the proposed CFLA approach is 1.664×10^{-3} which is significantly lower than the reduced order system achieved by MCS algorithm [1]. Performance criteria such as settling time, peak value, and performance indices such as ITAE, IAE, and ITSE are also calculated to demonstrate the efficacy of the proposed CFLA approach.

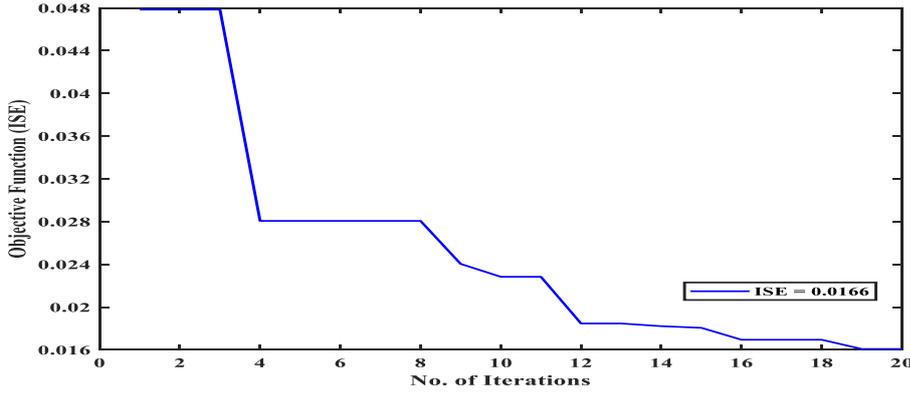


Fig. 12: Iteration Graph for Example 4.

Table 4: Performance comparison of original and reduced system for Example 4.

Methods	Peak Overshoot	Settling Time	ISE	ITSE	IAE	ITAE
Original System	1.0000	3.3637	–	–	–	–
Proposed Method	1.0304	7.5044	0.0166	0.0393	0.2954	1.0305
MCS [22]	1.0346	7.5435	0.0168	0.0396	0.2979	1.0314
SE - BB-BC [4]	1.0161	9.3120	0.0473	0.1007	0.4879	1.6033
MPC and GA [23]	1.01	5.1518	0.0586	0.8458	0.206	13.175
RMT [14]	0.99	6.9056	0.0877	0.1007	0.9359	14.425

Example 5. In this example a 4th order simple pole system of repeating poles is considered, whose transfer function is given below

$$G_4(s) = \frac{1}{(s+1)^4}$$

Third order reduced system by proposed technique (CFLA) given in section 3 is

$$R_3(s) = \frac{0.000573s + 0.2487}{s^3 + 1.4330s^2 + 0.9959s + 0.2487}$$

Third order reduced system obtained using Modified Cuckoo Search algorithm [1] in 2018 is as follows

$$R_3(s) = \frac{0.0001064s^2 + 0.2325}{s^3 + 1.238s^2 + 0.9371s + 0.2325}$$

Second order reduced system obtained using Modified Cuckoo Search algorithm [1] in 2018 is as follows

$$R_2(s) = \frac{0.1s + 0.1158}{s^2 + 0.5202s + 0.1158}$$

Figures 13 and 14 exhibit the step response and bode plot of the original and lower order models, respectively, to demonstrate the performance of the proposed CFLA approach. When comparing simulation results, the proposed third-order model utilising the CFLA approach is a better approximation to the original model than the second-order system. Comparative analysis of original and reduced system is depicted in Table 5. As shown in Table

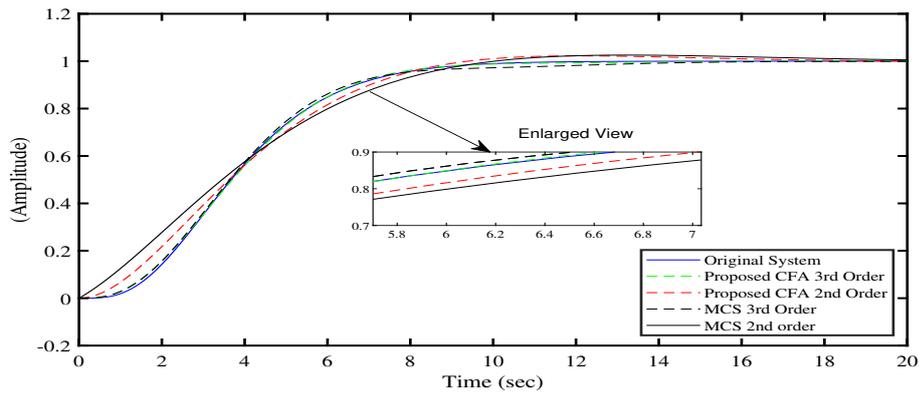


Fig. 13: Step response for Example 5.

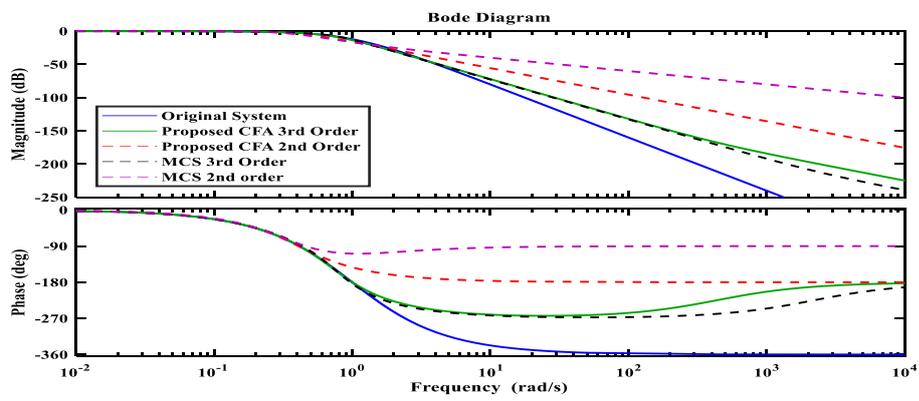


Fig. 14: Bode plot for Example 5.

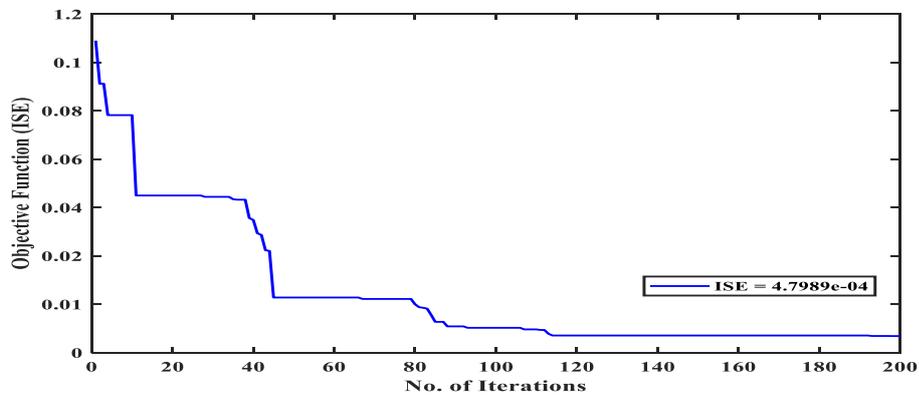


Fig. 15: Iteration Graph for Example 5.

5, the ISE value is significantly lower than the ISE value of a recently developed MCS algorithm [1]. As a result, it is discovered that the proposed third order model performs better compared to the recently developed techniques.

Table 5: Performance comparison of original and reduced system for Example 5.

Methods	Peak Overshoot	Settling Time	ISE	ITSE	IAE	ITAE
Original System	1.0000	9.0853	–	–	–	–
Proposed CFA 3 rd Order	0.9998	8.9736	$4.7989 * 10^{-04}$	0.0022	0.0729	0.5024
Proposed CFA 2 nd Order	1.0225	13.0202	0.0150	0.0692	0.4179	2.9084
MCS 3 rd Order [1]	0.9993	11.4912	0.0020	0.0173	0.1674	1.4252
MCS 2 nd Order [1]	1.0257	9.4118	0.0459	0.1585	0.6841	4.3022

Conclusion

The CFLA approach has been used to propose a novel technique for order reduction of higher order continuous time LTI systems. The coefficients of the reduced order model are obtained in the suggested study by using the ISE between the original higher order and reduced order models as the objective function. Five different higher order continuous time LTI systems were chosen in this study to determine their reduced order model using the suggested CFLA approach. In terms of step response and bode plot response, reduced models developed utilising suggested CFLA and existing MCS, RA and BB-BC, GA, FDA, ESA, LSMR, ESA and RA based algorithms are compared. The suggested CFLA-based reduction methodology provides more precise and steady performance than the other recently reported techniques, as evidenced by the time and frequency responses. Also the time response analysis is done for all the examples and tabulated in Tables 1 - 5. Further, ISE, ITSE, IAE and ITAE values are calculated with proposed CFLA method and found better than the other recently published reduced order methods.

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Conflict of interest

There is no any conflict of interest

Availability of data and material

No data and material is involved in the proposed work.

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