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Reduction of Continuous Interval Systems Using ISRAM

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Abstract

This research article suggests a novel procedure for representing the higher order system with its reduced order models of the desired order. The modelling of the systems by reducing the order of the system has been the requirement of the researchers for diminishing the computational effort and the execution time in critical missions of defence and space technologies. Many of the available methods in international literature suffer from the limitation of retention of the stability of the higher order system in its inheritance models. Few other methods have the disadvantage of framing the interval tables of full order and even the significant methods need the formation of two different tables at length for deriving the numerator and denominator polynomials of the models. Most of the physical applications of the modelling techniques require the matching of time and frequency responses of both the higher order and lower order systems, often fail to attain, but the suggested method guarantees the matching of the responses in addition to retaining the performance indicators such as Time-moments and Markov parameters. The impact of the suggested methodology is highlighted by retaining the Integral Square Error coefficient of the higher order system in its models, unlike other prominent methods available as the interval coefficients of the model become the subset of those of the higher order systems.

Keywords: Continuous Systems, Integral Square Error, Interval System, ISRAM, Kharitnov Polynomials, Model Order Reduction.

Introduction

Since recent years much effort has been made by the researchers towards the design of model reduction methods. In many engineering domains, the simplification of complicated systems is crucial. The methods available for the analysis of systems and the design are more effective and easily applied if the system are of low order whereas majority of practical systems are of very high order. Methods of order diminution can be broadly divided into two categories. Time and frequency domain order reduction techniques for a transfer function model are common. Particularly, for a state space template, time domain order diminution techniques are used. The literature contains several techniques for diminishing the order of linear continuous systems in both the frequency and time domains (1-5). The range of feasible outcomes is clearly provided by interval arithmetic both the automobile and aerospace sectors currently employ intervals to verify the best control software for on-board processors. For the order diminishing of interval systems in the continuous domain, a number of approaches have been studied. Some of these are Routh Pade Approximation (RPA), Stable Gamma Delta approximation and time moments and Markov parameters method, New Biased method suggested order diminution for higher order interval systems using a novel biased model. In $\gamma-\delta$ it is suggested to use the Routh approximation Method (RAM) for interval systems (6-10). This approach, which requires more computing work, uses both γ and δ tables to formulate diminished order numerator and denominator polynomials. This method involves the recursive nature of formulate for determining the reduced order models and obviously requires more computational efforts. Despite the fact that the initial High order interval systems (HOIS) is steady, the simplified model of the interval system is unsteady. The β and α tables yield the numerator and denominator of the diminished order model, correspondingly. The other relevant works can be referred in (11-23). Mathematical simplicity and time moment matching are two beneficial aspects of the simplified technique. More recently,

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Anderson based algorithm an innovative approach for lowering the order of High order continuous interval systems (HOCIS) has been developed (24). The Routh array and Anderson corollary are used to derive the model denominator. By comparing the calculated Markov Parameters (MPs) and time moments (TMs), the numerator is obtained. Additionally, straightforward generalized formulations are suggested for determining MPs and TMs in a way that eliminates the need for transfer function inversion. Kharitonov put up a novel method for handling interval approaches (25). By splitting the polynomials of intervals into its determined Kharitonov fixed coefficient polynomials, the Kharitonov's theorem can be applied to assess interval systems' stability. The interval system is considered stable if these local Kharitonov polynomials satisfy the stability criterion. The approach avoids the method from the selected parameters is achieved by a backward expansion of the D table first allowed by the N table unlike structured linear uncertain systems. The reduced mode obtained by the proposed new method still possess the stability preserving and time moment matching properties as in the SRAM . The proposed method is that the full impulse response energy of the original continuous time system is maintained in the approximant unlike structured linear uncertain systems. It avoids the two different algorithms are needed for obtaining both numerator and denominator polynomials of the reduced order models unlike γ-δ routh approximation for interval systems and structured linear uncertain systems reduction.

The suggested algorithm Improvement of simplified Routh approximation (ISRAM), besides simplifying the procedure by reducing the computations in deriving the numerator and denominator polynomials of the reduced order model, it also certain in retaining the stability unlike other methods available in the international literature. An additional feature is the method requires the formation of only one interval table where as other methods require the formation of two interval tables, also the single table can be terminated with the order of the model. Many of the available methods require the formation of the table in full even though the order of the model is much small. The interval ϕ parameters of the model are subset of those of the higher order system; this shows the retention of the singularities of the high order model in their reduced models. Furthermore, the suggested single input single output approach may further be employed to the discrete time system and multiple-input-multiple-output system.

The examples in this work of the article are meant to establish a comparison between the suggested approach and the methods currently in use, such as Kharitonov's polynomial method, Stability preservation method, Routh approximation method and Anderson corollary based new approximation method. In this work two instances are taken into consideration. Instance 1 is regarded to be the test system is fourth order interval system as it is meticulously used and got satisfactory results. Example 2 is deliberate to be is third order interval system has compared to proposed method with the vulgar existing methods.

Methodology

To transcend limitations and challenges of the contemporary strategy, a novel approach for reducing large scale interval systems for Single input single output (SISO) system. The suggested approach depends on the fundamental Routh Approximation (RA) concept (26). Consider a stable linear time- invariant interval framework represented by the transfer functions. Figure 1 explains the Flow chart for proposed ISRAM method. if the system order greater than 2, initially array design first, later integral square error used to identify reduced order model.

Routh array explains information for the Denominator. It is clearly presented in the procedural steps the algorithm needed for filling up of the coefficients of Routh array, the interval coefficients are being obtained from this array and the flow chart describes the protocol of steps to be followed for deriving the reduced order model.

$$G(s) = \frac{[X_0^-, X_0^+] + [X_1^-, X_1^+]S + \dots\dots\dots + [X_{n-1}^-, X_{n-1}^+]S^{n-1}}{[Y_0^-, Y_0^+] + [Y_1^-, Y_1^+]S + \dots\dots\dots + [Y_n^-, Y_n^+]S^n} \quad [1]$$

Step 1: Construct the Routh array for the denominator (Equation [1]).

$$[Y_1^-, Y_1^+][Y_2^-, Y_2^+][Y_3^-, Y_3^+]$$
$$[A_1^-, A_1^+][A_2^-, A_2^+][A_3^-, A_3^+]$$
$$[A_2^-, A_2^+][A_3^-, A_3^+]$$
$$[B_1^-, B_1^+][B_2^-, B_2^+]$$
$$[B_2^-, B_2^+]$$
……….

………

$$[C_1^-, C_1^+][C_2^-, C_2^+]$$
$$[C_2^-, C_2^+]$$

Where, i=odd

$$[A_i^-, A_i^+] = [Y_i^-, Y_i^+] \quad , i=1,3,5\ldots\ldots$$
$$[B_1^-, B_1^+] = [A_2^-, A_2^+]$$
$$[B_i^-, B_i^+] = [Y_{i+1}^-, Y_{i+1}^+] \ , \ i=1,3,5\ldots\ldots$$

Where, i= even

$$[A_i^-, A_i^+] = \frac{[Y_i^-, Y_i^+] - \{[Y_0^-, Y_0^+][Y_{i+1}^-, Y_{i+1}^+]\}}{[Y_1^-, Y_1^+]}$$
$$[B_i^-, B_i^+] = \frac{[A_{i+1}^-, A_{i+1}^+] - \{[A_1^-, A_1^+][A_{i+2}^-, A_{i+2}^+]\}}{[A_2^-, A_2^+]}$$

Step 2: The ϕ parameters are obtained from proportions of the ϕ array's first column components, as given in Equation [2]:

$$[\phi_1^-, \phi_1^+] = \frac{[Y_0^-, Y_0^+]}{[Y_1^-, Y_1^+]}$$
$$[\phi_2^-, \phi_2^+] = \frac{[A_1^-, A_1^+]}{[A_2^-, A_2^+]}$$
$$[\phi_3^-, \phi_3^+] = \frac{[B_1^-, B_1^+]}{[B_2^-, B_2^+]}$$
$$[\phi_n^-, \phi_n^+] = \frac{[C_1^-, C_1^+]}{[C_2^-, C_2^+]} \qquad [2]$$

Step 3: Find the numerator of the reduced order model (ROM), using Equation [3]:

$$N_k(S) = \frac{[\phi_K^-, \phi_K^+]}{[Y_0^-, Y_0^+]}\{[X_0^-, X_0^+] + [X_1^-, X_1^+]S + \ldots.. + [X_{K-1}^-, X_{K-1}^+]S^{K-1}\} \qquad [3]$$

Where, $N_k(s)$ = k^{th} order Numerator.

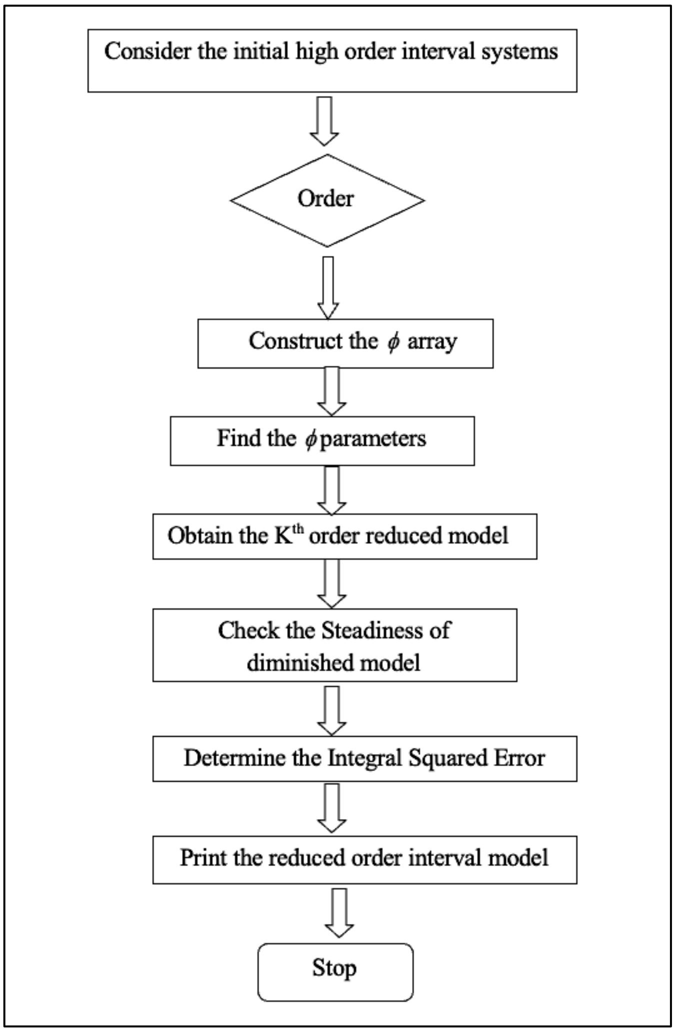

Figure 1: Flow chart for proposed ISRAM

Step 4: Find the denominator of the ROM (Equation [4]):

$$D_k(S) = [1,1]S^K + \frac{[\phi_K^-, \phi_K^+]}{[Y_0^-, Y_0^+]}\{[Y_0^-, Y_0^+] + [Y_1^-, Y_1^+]S + \ldots\ldots + [Y_K^-, Y_K^+]S^K\} \quad [4]$$

$D_k(s)$ = Kth order denominator.

Step 5: The transfer function then defines the Kth order simplified model for this system (Equation [5]).

$$R_K(S) = \frac{[x_0^-, x_0^+] + [x_1^-, x_1^+]S + \ldots\ldots + [x_{K-1}^-, x_{K-1}^+]S^{K-1}}{[y_0^-, y_0^+] + [y_1^-, y_1^+]S + \ldots\ldots + [y_K^-, y_K^+]S^K} = \frac{N_K(S)}{D_K(S)} \quad [5]$$

Where k = 1,2……n

Step 6: Use the Routh-Hurwitz stability criterion to determine whether the ROM $R_K(S)$ is stable when the characteristic polynomial's coefficients are known. Kharitonov's theorem can be used when the coefficients are only known to fall within specific ranges. Routh-Hurwitz is concerned with an ordinary polynomial, whereas it assesses stability for an interval polynomial.

Step 7: Integral Squared Error (ISE); The form shows the ISE with in the low order system (LOS) and the original high order system (HOS), as given in Equation [6].

$$ISE = \int_0^\infty [g(t) - g_K(t)]^2 \, dt \quad [6]$$

Where, g (t) = Output of original high order systems, g_k (t) = Output of k^{th} order at the specified time instant. The procedure for drawing the interval table is non-repetitive in nature and the required coefficient can directly be calculated. The digital code for developing the reduced order model can be prepared following the presented flowchart.

Results and Discussion

Example 1:

Examine an 4^{th} order interval system of higher order representing a physical case of engineering, as given in Equation [7]:

$$G(S) = \frac{[28,29]S^3 + [496,497]S^2 + [1800.1801]S + [2400,2401]}{[2,3]S^4 + [36,37]S^3 + [204,205]S^2 + [360,361]S + [240,241]} \quad [7]$$

ϕ interval parameters are obtained by Equation [8]:

ϕ_1 = [0.6648, 0.6694]

ϕ_2 = [1.9889, 2.0141]

ϕ_3 = [5.4206, 6.0418]

ϕ_4 = [9.9858, 16.5110] [8]

The reduced numerator obtained by step 3 (Equation [9])

$$N_2(S) = [26.1, 30.2568]\ S + [34.8, 40.3368] \quad [9]$$

The step 4-obtained reduced denominator, given as Equation [10]:

$$D_2(S) = [1, 1]\ S^2 + [5.22, 6.0648]\ S + [3.4952, 4.0443] \quad [10]$$

Using the suggested approach and using the Equation [3, 4] the second order diminished model acquired by retaining ϕ_1 and ϕ_3 values of the original system is given as in Equation [11]:

$$R_2(S) = \frac{[26.1,30.2568]S + [34.8,40.3368]}{[1,1]S^2 + [5.22,6.0648]S + [3.4952,4.0443]} \quad [11]$$

Check the Stability of the above transfer function using Kharitonov's theorem. For both the HOM and ROM, the step response and impulse response have been acquired in order to examine the system's behavior in both steady state and transient states.

Table 1: Comparison of [$\phi^- \phi^+$] Specifications of Original HOIS and Its ROM

[$\phi^- \phi^+$]Parameters	Original high order systems	3^{rd} order reduced model [$\phi_1 \phi_2 \phi_4$]	2^{nd} order reduced model [$\phi_1 \phi_3$]
First	[0.66482, 0.6694]	[0.3941, 1.1291]	[0.59039, 0.7538]
Second	[1.9882, 2.0141]	[1.0587, 3.3343]	
Third	[5.4273, 6.0441]		[5.3898, 6.08615]
Fourth	[9.985, 16.51178]	[5.9132, 18.6228]	

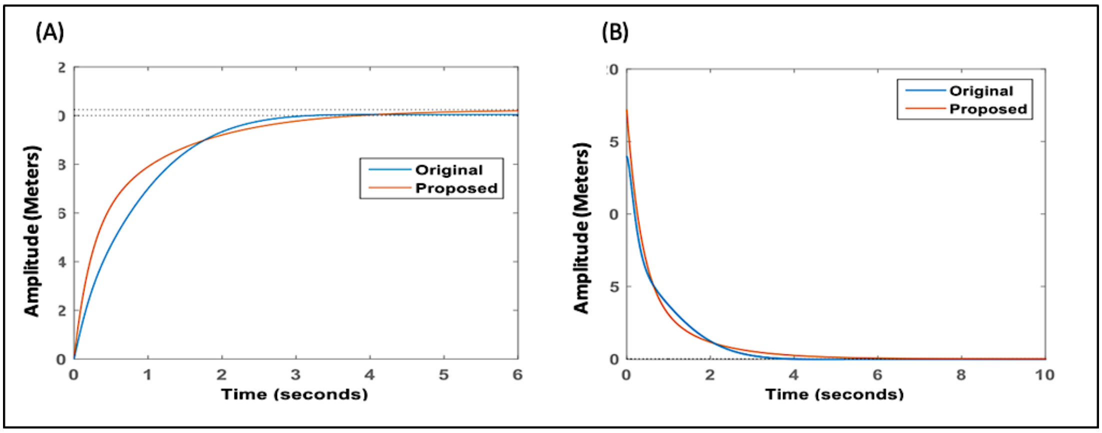

Figure 2: Contrast Analysis of Responses: (A) Step Responses of Higher and 2nd order Lower Bound Proposed Model, (B) Impulse Response of Higher and 2nd Order Proposed Templates of Lower Bound

Table 1 shows that the comparison of ϕ interval parameters of original and 2nd, 3rd order reduced models. A contrast analysis of step and impulse responses of high order system (HOS) and Low order model (LOM) acquired by is shown in Figures 2 to 5. From Figures, it is evident that the LOM response produced by the suggested method is substantially more similar to the original system. As may be seen, in Table 1, the $[\phi^{-}\phi^{+}]$ parameters of the inception HOS and its diminished order interval templates are all positive intervals. In its lower order models, this guarantees that the stability of the original HOIS is maintained.

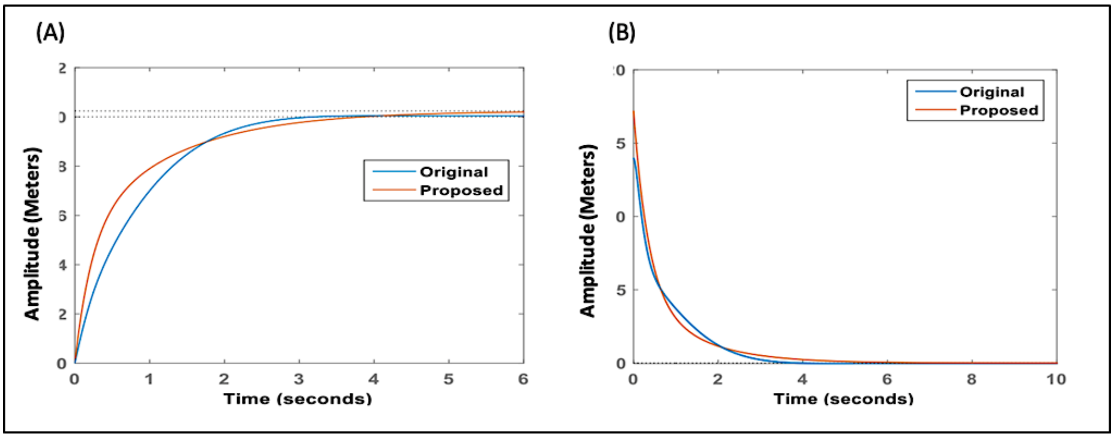

Figure 3: Contrast Analysis of Responses: (A) Step Responses of the HOM and ROM of Upper Bound, (B) Impulse Responses of the HOM and ROM of Upper Bounds

Figures 2A and 3A demonstrate the step response of the HOM and ROM Kharitonov polynomial of lower bound and upper bound. The impulse response is obtained in order to investigate the system with sudden disturbance. Figures 2B and 3B demonstrate the Kharitonov's polynomial's impulse response for both the HOM and ROM. The impulse response has been determined for both the higher and lower order models, much like the step response analysis. The HOM response curves in this case also contain ROM response curves.

Example 2 :-(Comparing with other Current Approaches)

Examine the following HOIS of third order interval system (27), as given in Equation [12]:

$$G(S)=\frac{[2,3]S^2+[17.5,18.5]S+[15,16]}{[2,3]S^3+[17,18]S^2+[35,36]S+[20.5,21.5]} \quad [12]$$

Using the proposed ϕ table, the ϕ interval parameters are obtained as in Equation [13]:

ϕ_1 = [0.5694, 0.6142], ϕ_2 = [2.1661, 2.2696] and ϕ_3 = [5.287, 8.079] [13]

Utilizing the suggested approach, for K=2 retaining ϕ_1 and ϕ_3 values, the appropriate template of diminished order is derived as given in Equation [14]:

$$R_2(S) = \frac{[2.45,4.477]S + [2.1,3.872]}{[1,1]S^2 + [4.9,8.712]S + [2.87,5.203]} \qquad [14]$$

Using Kharitonov's polynomial approach (21) to approximate the impulse energy of a HOIS, for K=2 the corresponding ROM is obtained as given in Equation [15]:

$$R_2^I(S) = \frac{[1.172,1.3682]S + [1.0269,1.1097]}{[1,1]S^2 + [2.344,2.6232]S + [1.14,1.26]} \qquad [15]$$

Employing stability preservation techniques (18) to reduce the order of HOIS for K=2 the corresponding reduced order model is obtained by Equation [16]:

$$R_2^{II}(S) = \frac{[1.038,1.221]S + [0.87,1.09]}{[1,1]S^2 + [2.08,2.38]S + [1.18,1.46]} \qquad [16]$$

Using the Routh Pade Approximation for interval system method (9) for K=2, the corresponding ROM is obtained by Equation [17]:

$$R_2^{III}(S) = \frac{[1.01,1.26]S + [0.84,1.12]}{[1,1]S^2 + [2.02,2.44]S + [1.15,1.15]} \qquad [17]$$

Using the Anderson corollory based on new approximation method (20) for K=2, the corresponding ROM is obtained as given in Equation [18]:

$$R_2^{IIII}(S) = \frac{[12.5,16.8]S + [15.35,16.38]}{[1,1]S^2 + [31.2,31.2]S + [21.5,21.5]} \qquad [18]$$

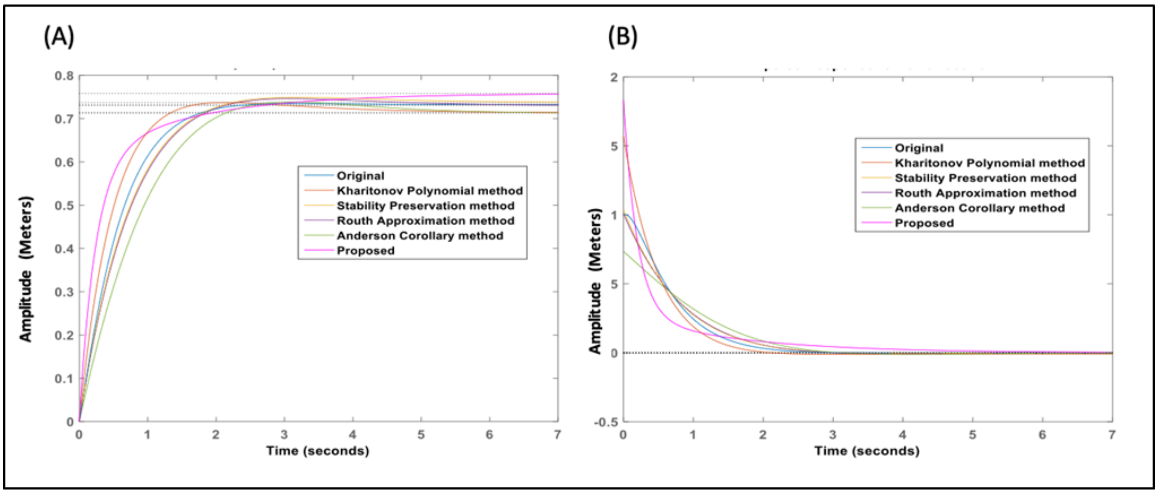

Figure 4: Contrast Analysis of Responses - (A) Comparing Step Responses of HOS And Various 2nd Order Reduced Templates of Lower Bound, (B) Comparing Impulse Responses of Higher And Various 2nd Order Reduced Templates of Lower Bound

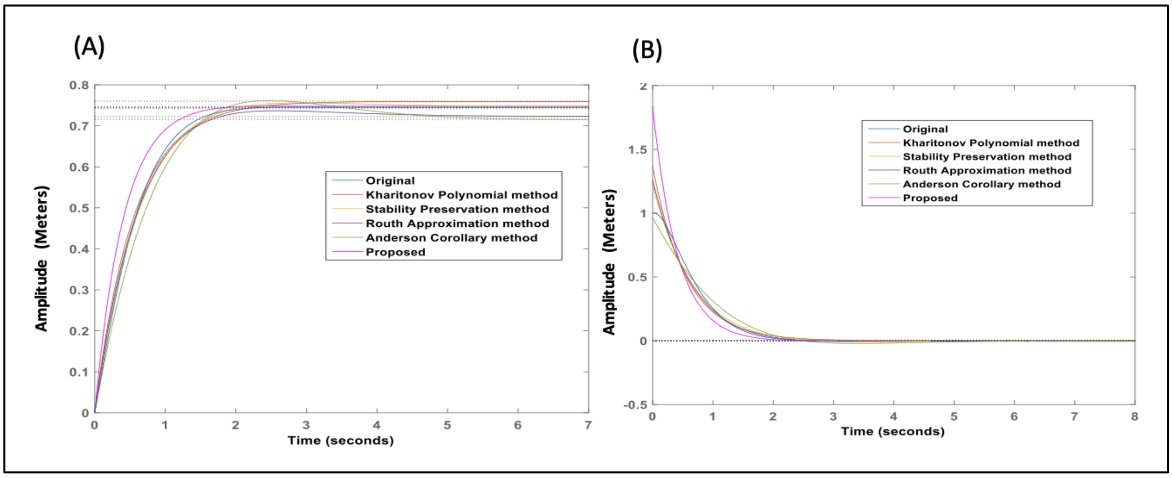

Figure 5: Contrast Analysis of Responses: (A) Comparing Step Responses of the HOM and ROM of Upper Bound, (B) Comparing Impulse Responses of the HOM and ROM of Upper Bound

The contrast between step and impulse responses of various LOMs and HOS as shown in Figures 4A, 4B, 5A and 5B. Figures make it evident that, in comparison to other methods now in use, the suggested model provides the best degree of accuracy. This demonstrates the suggested algorithm's efficacy and comparison of the Integrated Squared Error values of the proposed method, Kharitonov's polynomial method, Stability preservation method and Routh Pade approximation method.

For supporting analysis, the obtained error indices are displayed as ISE. Both lower and upper restrictions are taken into account when calculating the performance indexes. The performance indices are tallied in Table 2.

Table 2 demonstrates that the suggested approach reduced order model (ROM) and High order model (HOM) coefficients with less error compared to the alternative techniques. Compared proposed method, Kharitonov's polynomial method, Stability preservation method, Routh approximation method and Anderson corollary based on new approximation method, the Integrated squared error of the proposed method is very low. The results shown in Table 2 attest to the efficacy of the suggested approach.

From all the Figures, it is may be suggested that the proposed method response is very much close to the original method response, integral square error also minimises in greater extent. This will concludes the proposed system superiority over other methods.

Table 2: Model Order Reduction Method Error Analysis

Transfer function	Model	ISE Values
$R_2(S)=\dfrac{[2.45,4.477]S+[2.1,3.872]}{[1,1]S^2+[4.9,8.712]S+[2.87,5.203]}$	Proposed	[0.8951, 0.9528]
$R_2^{I}(S)=\dfrac{[1.172,1.3682]S+[1.0269,1.1097]}{[1,1]S^2+[2.344,2.6232]S+[1.14,1.26]}$	Kharitonov's Polynomial Method	[1.150, 1.232]
$R_2^{II}(S)=\dfrac{[1.038,1.221]S+[0.87,1.09]}{[1,1]S^2+[2.08,2.38]S+[1.18,1.46]}$	Stability Preservation Approach	[1.0251, 1.1218]
$R_2^{III}(S)=\dfrac{[1.01,1.26]S+[0.84,1.12]}{[1,1]S^2+[2.02,2.44]S+[1.15,1.15]}$	Routh Approximation Method	[1.1263, 1.2639]
$R^{IIII}(S)=\dfrac{[12.5,16.8]S+[15.35,16.38]}{17S^2+31.2S+21.5}$	Anderson Corollary based on New Approximation Method	[0.9981, 0.9981]

Table 2 shows the comparison of the Integral Square Errors of the models obtained by using the suggested procedure and other significant and widely used procedures available in international literature. The ISE and the step responses are given for the relative units of the respective magnitudes of the system output considered.

Conclusion

New developments and applications of algorithm for the diminution of high order low interval systems (HOLIS). The suggested approach gets beyond some of the confinements and flaws in few of the contemporary techniques. The recommended strategy is efficient since it only prerequisites the creation of one Routh array and eliminates the need to create two suggestive measures. This approach also eliminates the need for complicated matrix calculations and the prior computation of time moments and Markov parameters of the original HOLIS. The suggested algorithm is validated using illustrative instances and its outcomes are contrasted with those of other approaches. The proposed method always generates stable reduced order models for stable original high order systems hence always retains stability of original system in its low order models. In this method, requires only one table and avoids the necessity of formulation of two separate tables. This method avoids the necessity of formulation of separation of numerator and denominator polynomials of original high order systems with the structured linear uncertain systems. It does not involve the reciprocal transfer function with structured linear uncertain systems reduction and model reduction of linear interval system using pade approximation.

The accuracy and relevance of the suggested strategy are illustrated by the outcomes acquired and the comparative evaluation is carried out using the integral square error values.

Abbreviations

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Author Contributions

Nagalla Sowjanya: methodology, software, validation, formal analysis, research, resources, data curation, writing—original draft preparation, writing—review & editing, project administration, D Vijay Kumar: supervision, P Mallikarjuna Rao: supervision. The authors have reviewed and approved the manuscript's published version.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability

Data are available from the corresponding author on a reasonable request.

Declaration of Artificial Intelligence (AI) Assistance

All content was created solely by the authors. Authors declared that no AI tools used while preparing manuscript.

Ethics Approval

Not Applicable.

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