Order Reduction of Discrete System Models Employing Mixed Conventional Techniques and Evolutionary Techniques

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Abstract A single-input single-output discrete system of high order is reduced to a second order in this paper employing two approaches: an indirect approach using conventional techniques and a direct approach using evolutionary techniques. In the indirect approach, the discrete system is transformed to a continuous system and reduced to a lower order by Padê approximation (by matching Time Moments or Markov parameters) combined with Routh approximation for ensuring stability and inverse transformed back to a lower order discrete system. In the evolutionary approach, the discrete system is reduced to a lower order discrete function and optimized based on minimization of ISE as the objective function using Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) independently. The step responses of reduced order discrete systems obtained by the conventional and evolutionary approaches are compared to determine the best solution.

1 Introduction

For analysis, synthesis, and to study the behavior of real-life systems, its high order complex mathematical model needs to be reduced to simpler lower order model whose behavior resembles that of original system as far as feasible. Various methods of model order reduction have been listed and described comprehensively

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and comparatively by Genesio R. et al. and other authors [1–7]. Shamash Y. [7] showed that the models reduced from even the originally stable models by many methods are not always stable. This problem has been addressed by Hutton M and many others [8–26] by reduction methods using stability criterion like Routh approximation or Mihailov stability criterion and many without the aid of any stability criterion as well as using mixed techniques. Majority of various methods referred above are applicable for reduction of continuous systems only. The discrete systems can be reduced in discrete domain directly or indirectly using known conventional methods and their stability verified [27–33]. In the last two decades, bio-inspired evolutionary techniques such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO) method have emerged as modern tools for reduction and optimization [34–42]. In this paper, an nth-order single-input single-output discrete system has been reduced by two approaches. The first indirect approach consists of the transformation of the discrete system into a continuous system, order reduction of the continuous system using a combination of conventional techniques of Padé approximation (by matching Time Moments or Markov parameters) combined with Routh approximation for ensuring stability, and inverse transformation of the reduced continuous system back into a discrete system. The second approach consists of the direct method using evolutionary techniques of GA and PSO independently. This paper is organized into eight major sections with Sect. 1 already used for introduction. The problem statement is made in Sect. 2. Indirect approach of order reduction by a combination of conventional techniques has been presented in Sect. 3. In Sects. 4 and 5, order reduction and optimization of the solution by GA and PSO methods have been presented sequentially. All the above methods have been applied to an eighth-order discrete transfer function to obtain second-order reduced discrete transfer function in Sect. 6. The results obtained are compared in Sect. 7. Conclusions made are discussed in Sect. 8.

2 Problem Statement

An nth-order discrete system transfer function in z-transform is represented by:

$$G(z) = N(z)/D(z). \tag{1}$$

with numerator $N(z) = a_0 + a_1 z + a_2 z^2 + \cdots + a_{(n-1)} z^{(n-1)}$ and denominator $D(z) = b_0 + b_1 z + b_2 z^2 + \cdots + b_{(n-1)} z^{(n-1)} + b_n z^n$ where a_i $(0 \leq i \leq n - 1)$ and b_i $(0 \leq i \leq n)$ are the scalar coefficients of powers of 'z' in the expressions of numerator $N(z)$ and denominator $D(z)$, respectively.

The main objective is to derive a discrete system transfer function $R(z)$ of lower order 'r' $(r < n)$ using indirect (conventional) methods and direct methods (GA and PSO). The reduced transfer function is represented by

$$R(z) = N_r(z)/D_r(z). \tag{2}$$

with numerator $N_r(z) = c_0 + c_1 z + c_2 z^2 + \cdots + c_{(r-1)} z^{(r-1)}$ and denominator $D_r(z) = d_0 + d_1 z + d_2 z^2 + \cdots + d_{(r-1)} z^{(r-1)} + d_r z^r$ where c_i $(0 \leq i \leq r-1)$ and d_i $(0 \leq i \leq r)$ are the scalar coefficients of powers of 'z' in the expressions $N_r(z)$ and $D_r(z)$ respectively chosen such that the behavior and response of $R(z)$ should match as closely as possible to that of $G(z)$ for the same type of inputs.

3 Reduction by Conventional Method

Verify the stability of discrete system G(z) by applying Jury stability criterion. By applying bilinear transformation $z = (1 + s)/(1 - s)$ to G(z) to Eq. (1), obtain an equivalent continuous system transfer function G(s) represented by Eq. (3) given below

$$G(s) = N(s)/D(s). \tag{3}$$

with numerator $N(s) = e_0 + e_1 s + e_2 s^2 + \cdots + e_{(n-1)} s^{(n-1)}$ and denominator $D(s) = f_0 + f_1 s + f_2 s^2 + \cdots + f_{(n-1)} s^{(n-1)} + f_n s^n$ where e_i $(0 \leq i \leq n-1)$ and f_i $(0 \leq i \leq n-1)$ are the scalar coefficients of powers of 's' in the expressions $N(s)$ and $D(s)$, respectively.

Construct Routh array from the denominator $D(s)$ by arranging the powers of s in the decreasing order. Verify the stability the $G(s)$ by applying Routh stability criterion. Using Routh approximation method proposed by Hutton and Friedland, modified by Shamas Y and illustrated by Panda S. et al. [8, 9, 40], obtain a reduced order denominator of desired order 'r' as shown below in Eq. (4):

$$D_r(s) = \left\{ \sum_{j=0}^{r} h_j s^j \right\} \text{ with } h_r = 1. \tag{4}$$

Following John S. et al. and Panda S. et al. [12, 14, 40], $G(s)$ is expanded about $s = 0$ (or $s = \infty$) into power series with time moments (or Markov Parameters) given below:

Time Moment power series $G(s) = G_T(s) = \left(p_0 + p_1 s + p_2 s^2 + p_3 s^3 \ldots \right).$ (5)

and Markov Parameters power series $G(s) = G_M(s) = (m_1 s^{-1} + m_2 s^{-2} + m_3 s^{-3} \ldots).$

(6)

Multiply the power series Eqs. (5) and (6) independently with the reduced denominators $D_r(s)$ Eq. (4) and limit the largest power of s in the products to one

power less than that of the reduced denominator Eq. (4) to obtain the two reduced numerators as given below in Eq. (7):

$$N_r(s) = \left[\sum_{j=0}^{r-1} \left(q_j s^j\right)\right] \tag{7}$$

where j represents power of s and q_j represent the coefficient of jth power of s. By using reduced numerators and reduced denominator represented by Eqs. (7) and (4), obtain two reduced models of order 'r' in s domain, one model by matching Time Moments in Eq. (5) and one model by matching Markov parameters in Eq. (6), as given below in Eq. (8):

$$G_r(s) = N_r(s)/D_r(s) \tag{8}$$

Remove the steady state errors of the reduced functions by multiplying the reduced functions with respective gain correction factors $[G(s)/G_r(s)]_{s=0}$. Convert the reduced models in s domain to z domain by inverse bilinear transformation yielding four reduced discrete functions $G_r(z)$ by the indirect conventional approach. Once again steady-state errors are removed by applying suitable correction factors. Finally, verify the stability of each of the reduced discrete function $G_r(z)$ by determining that all the discrete system poles reside inside the area of circle of radius $|z| = 1$.

4 Reduction by GA Technique

The objective function chosen in this paper for the GA technique is minimization of the (ISE) or square of error between the transient state step responses of the original discrete system $G(z)$ of high order and the reduced order discrete system $R(z)$ integrated within the limits of time domain of transient state. The ISE computed by the integral I given by Eq. (9) is as follows:

$$I = \int_0^{T_s} [y(t) - y_r(t)]^2 d(t) \tag{9}$$

where $y_r(t)$ and $y_r(t)$ represent the unit step responses of original and desired reduced discrete transfer functions and T_S represents the settling time of transient state response. The evolution in GA is initiated from a population of randomly generated variables. The reduced order transfer function $R(z)$ is optimized through a number of iterations (generations). For a given optimization objective function, a number of solutions are possible.

An optimized reduced function of desired order is obtained using readily available MATLAB code for GA after defining the objective function, controlled variables, maximum number of generations, population size as well as the upper and lower bounds of each variable. The controlled variables are the scalar coefficients of powers of z in the numerator and denominator of the desired reduced discrete system transfer function arranged in a defined sequence. Their total number of controlled variables is five (5) for optimizing second-order reduced function. GA creates new solutions (akin to chromosomes of a living cell) using reproduction, crossover, and mutation.

5 Reduction by PSO Technique

In the PSO method, the reduced order transfer function R(z) is optimized through a number of iterations (generations) keeping an optimization objective. A number of feasible solutions (called as a particles) are produced in each generation by following the principles of fish schooling or flocking behavior of birds or social behavior of a flock of birds. The objective function of the PSO method is also the same as in the case of the GA method and is given by Eq. (9).

Each particle endeavors to improve its fitness in each successive generation by imitating the properties of more successful peers. It is capable of remembering its own best fitness position (referred to as the *p-best*) in the solution space so far visited by it. The overall best fitness position out of all the *p-best* positions of different particles in the population in a given generation is called as the group best or the g-*best* position. Each particle continuously makes effort to move toward the g-*best* position. Each particle flies in the solution space with a velocity determined by its own momentum which is modified dynamically according to its own flying experience (p-best position) (cognitive vector) as well as that of its peers or other particles (g-best position) (social vector). Various parameters are selected carefully according to past experience to guide the particle achieve an optimum value as fast as possible with suitable velocity and without resorting to excessive iterations. The PSO algorithm needs to be initialized with an initial swarm consisting of the coefficients of powers of z chosen from any known reduced discrete system of desired order. In each PSO run, the optimization ceases automatically after completing the preset number of generations (iterations). Barring the first PSO run, the initialization of the next PSO run is done using the optimized results achieved in the previous PSO run. The ISE will gradually reduce and get stabilized with the increase in the execution of a total number of iterations.

6 Numerical Example

6.1 Combined Routh Approximation and Padê Approximation Method

An eighth-order discrete system (converted from an eighth-order stable continuous system of Panda S. et al. [40]) is given in Eq. (10) as shown below:

$$G(z) = N(z)/D(z) \text{ with a sampling period of 0.25 s} \tag{10}$$

where $N(z) = 2.052\ z^7 - 5.461\ z^6 + 4.64\ z^5 - 0.04639\ z^4 - 2.228\ z^3 + 1.25\ z^2 - 0.1686\ z - 0.02627$ and $D(z) = z^8 - 3.044\ z^7 + 3.877\ z^6 - 2.697\ z^5 + 1.12\ z^4 - 0.2842\ z^3 + 0.04307\ z^2 - 0.003565\ z + 0.0001234$. The main objective is to derive a stable reduced second-order discrete system model which has a transient step response similar and as close as possible to that of the original stable discrete system of eighth order. The steps explained in Sect. 3 have been implemented on the eighth-order discrete transfer function (10) to obtain stable second-order reduced discrete transfer functions by the indirect conventional method as given below:

$$R_{TM}(z) = (1.632z - 0.5788)/(z^2 + 0.01711z + 0.0001234) \tag{11}$$

$$R_{MP}(z) = (1.142z - 0.0886)/(z^2 + 0.01711z + 0.0001234) \tag{12}$$

6.2 Genetic Algorithm Method

An optimized second-order discrete transfer function as shown below in Eq. (13) is obtained by running a GA program readily available on MATLAB after specifying various parameters, defining the objective function and entering the coefficients of powers of z of Eq. (10) in predefined sequence:

$$R_{GA}(z) = (1.3048z + 0.6109)/(1.0071z^2 + 0.2104z + 0.5314) \tag{13}$$

6.3 Particle Swarm Optimization Method

The coefficients of powers of z of the second-order reduced function $R_{T1}(z)$ Eq. (11) obtained by the conventional methods is used for initialization of PSO algorithm. An objective function is defined and various parameters are specified in Sect. 5. A program based on PSO algorithm is run on MATLAB after entering the coefficients of powers of z of Eq. (10) in the program. The reduced function obtained in

a particular run is used for initialization of next PSO run and so on for subsequent runs. The second-order reduced discrete function obtained by PSO is given in Eq. (14) shown below.

$$R_{TMPSO}(z) = \frac{(-69.1165743z + 63.03683816)}{(-38.17950153z^2 + 43.06414420z - 10.78699324)} \quad (14)$$

The plot of ISE data generated during seven consecutive PSO runs versus the generation number in Fig. 1 shows optimization of solutions after 200 generations, the minimization, and the convergence of ISE data with an increase in the number of generations. In a similar manner, using the discrete second-order functions $R_{M1}(z)$ Eq. (12) for initialization of PSO, another second-order reduced optimized discrete transfer function is obtained as shown below in Eq. (15).

$$R_{MPPSO}(z) = \frac{(6.14176748z - 5.58841660)}{(3.65282698z^2 - 4.30474654z + 1.18888032)} \quad (15)$$

The step responses of second-order discrete system equations obtained by the second-order Eqs. (14) and (15) obtained by PSO, paired with Eqs. (11) and (12) obtained by indirect conventional method (by matching Time Moments or Markov parameters) combined with Routh approximation and Eq. (13) obtained by GA, along with original discrete eighth-order Eq. (10) are plotted in Figs. 2 and 3. The parameters of step responses, viz., settling time (T_S), rise time (T_R), peak time (T_P), and maximum overshoot (M_P) are measured from the plots of step responses. The values of poles for each transfer function are calculated. The ISE values are calculated for all the reduced second-order functions using Eq. (9). The results obtained are tabulated in Table 1 for comparison.
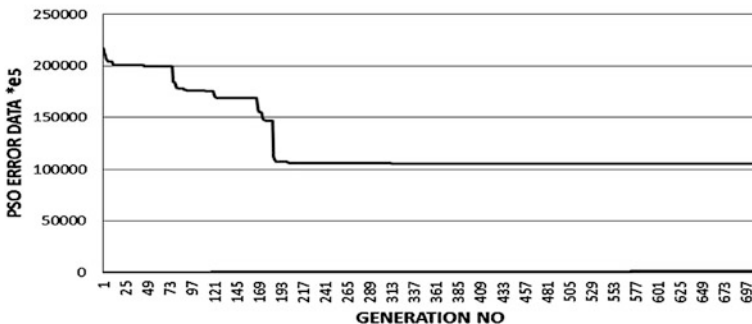

Fig. 1 ISE (between original transfer function and reduced function) versus PSO Generation No
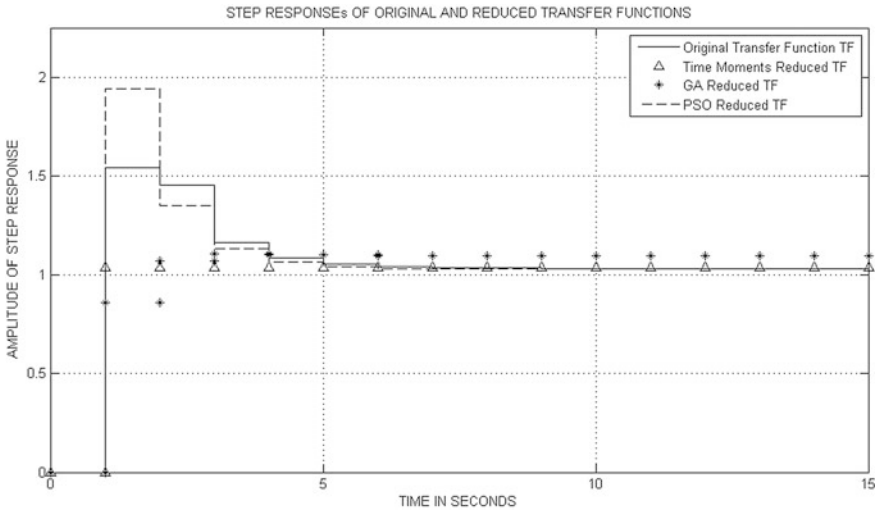
Fig. 2 Step responses of original discrete TF, reduced TF matched with time moments, GA reduced TF, and PSO reduced TF
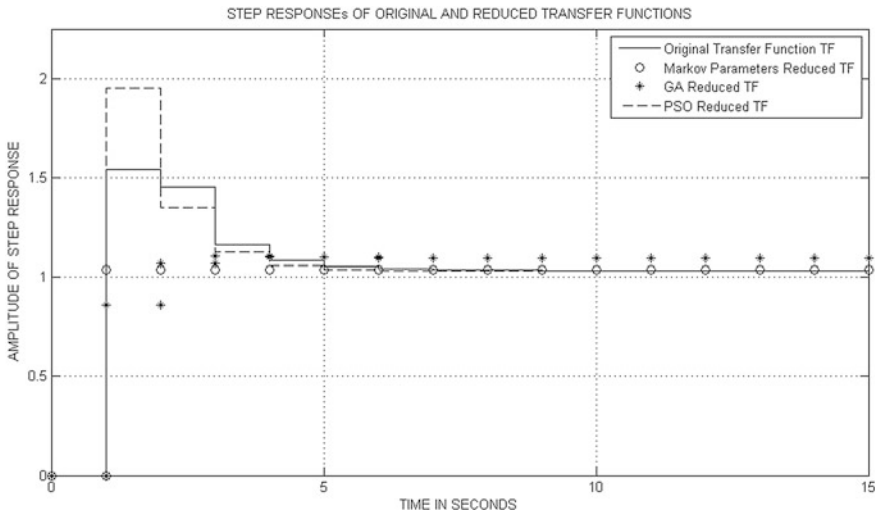

Fig. 3 Step responses of original discrete TF, reduced TF matched with Markov parameters, GA reduced TF and PSO reduced TF

Table 1 Comparison of step response parameters and poles of the original transfer function (OTF) and reduced functions TMTF, MPTF, GATF, and PSO RTF

Transfer function	T_R (s)	T_P (s)	M_P (%)	T_S (s)	ISE	Poles
Original eighth order Eq. (10) (OTF) G(z)	1.0	1.0	54	5.5	NA	0.7838, 0.6236, 0.4462 $\pm$ j0.1099, 0.2256 $\pm$ j0.0717, 0.1577, 0.1353
Reduced 2nd order $R_{TM}(z)$ Eq. (11)	1.0	1.0	3.54	1.0	0.3670	$-0.0086 \pm$ j0.0071
Reduced 2nd order $R_{MP}(z)$ Eq. (12)	1.0	1.0	3.56	1.0	0.6486	$-0.0086 \pm$ j0.0071
Reduced 2nd order $R_{GA}(z)$ Eq. (13)	1.0	3.0	10	4	0.0261	$-0.1045 \pm$ j0.7188
Reduced 2nd order $R_{TMPSO}(z)$ Eq. (14)	1.0	1.0	94	4.5	0.00067	0.7525 and 0.3755
Reduced 2nd order $R_{MPPSO}(z)$ Eq. (15)	1.0	1.0	95	4.5	0.0047	0.7367 and 0.4418

7 Discussion of Results and Comparison of Methods

It can be seen from Figs. 2, 3 and Table 1 that the magnitude of each of the poles of all functions is less than unity and lie within the unit circle. All the 2nd order Reduced Transfer Functions (RTFs) are stable like the 8th order Original Transfer Function (OTF). But the dominant poles of the PSO reduced RTFs are closer to that of the OTF. Though the step responses of all the RTFs have zero steady-state error, the amount of similarity and close resemblance of the shapes of step responses vary from one RTF to another. While the step response of OTF has a distinct large overshoot and the overshoots in step responses of RTFs due to GA and other conventional methods are insignificant, but the step responses of RTFs only due to PSO has got some significant values of overshoots comparable and even larger than that of 8th order OTF. On comparison of step response parameters settling time (T_s), maximum overshoot (M_p), peak time (T_p), and rise time (T_R) and ISE, it can be seen that the parameters of step responses of RTF obtained by PSO are the closest and best approximates of OTF, while those obtained by GA Padê and Routh approximations are quite inferior and poor approximates of 8th order OTF.

8 Conclusion

In this work, a discrete system transfer function of eighth order has been reduced to a discrete transfer function of second order by the indirect approach of combined conventional methods of Padê approximation (matching of Time Moments/Markov parameters) and Routh approximation and direct methods of Genetic Algorithm and Particle Swarm Optimization. A comparison of all parameters and the step

responses shows that the results of the discrete functions reduced by PSO method are best and closest approximates of original model followed by that of GA method and the step responses of the reduced TF obtained by conventional techniques are poor approximates of the step response of original transfer function. This is also confirmed by the lowest ranges of ISE of the PSO reduced functions.

Therefore, it can be concluded that the PSO technique is the best of all the methods of reduction discussed above. Considering that the reduction is from a high eighth order to a low second order, the results are satisfactory and encouraging. Still better results and closer resemblance of step response of RTFs with that of OTF can be expected if the desired order of reduced function is increased to third order or higher.

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