

Lecture Notes in Mechanical Engineering

Ravipudi Venkata Rao  
Samir Khatir  
Thanh Cuong-Le *Editors*

# Recent Advances in Structural Health Monitoring and Engineering Structures


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# Lecture Notes in Mechanical Engineering


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Ravipudi Venkata Rao · Samir Khatir ·  
Thanh Cuong-Le  
Editors

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*Editors*

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# Weight Optimization of Truss Structures with Different Constraints Using Rao Algorithms and Their Variants



Zinzuvadia Niketkumar Maheshkumar, Ravipudi Venkata Rao,  
Samir Khatir, and Thanh Cuong-Le

## 1 Introduction

In structural optimization, designers look for an optimal solution that creates a structure that sustains the loads while satisfying the constraints. Generally, the objective of the structural optimization problem is to optimize the weight and strength while meeting the constraints of displacement at nodes, stress in the bars or natural frequency of the structure. The size, shape and topology optimization are three divisions of structural optimization. If the truss design is considered, then in size optimization, the design variables are the cross-sectional areas of the truss members. In the shape optimization problem, the location of the truss nodes is under study, and in topology optimization, the connectivity of the truss members is under investigation. In the present work, two weight optimization problems of ten bar truss structure are considered. One problem is solved with the natural frequency constraints, and the other is solved with the constraints related to the nodal displacement and the stress in the truss members.

Truss structure optimization has received the interest of researchers because it optimizes the size of the truss resulting in less manufacturing cost and yields better dynamic behavior using natural frequency constraints. In a truss optimization problem, the natural frequency is restricted in a certain range to avoid the phenomenon of resonance. Along with the required dynamic response, engineering

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structures should also be light in weight [1]. The designer can control the frequency of the truss structure in the desired manner to improve the dynamic behavior. The size optimization of truss is a complex problem and consideration of natural frequency as constraints increase the complexity of the problem [2]. Similarly, the truss optimization problem with constraints related to the nodal displacement and the stress in the truss members minimizes the weight of the truss, and it also assures that the truss performs satisfactorily in its application. Researchers have proposed different methods in the past to address the complexity of the truss optimization problem.

Sedaghati et al. [3] solved the frame and truss structure optimization problem with frequency constraints using combined finite element-based technique and sequential quadratic programming. Gholizadeh et al. [4] used genetic algorithm and Salajegheh et al. [5] solved structure optimization problems under multiple natural frequency constraints with a neural network. Gomes [6] optimized the shape and size of the truss structure using particle swarm optimization algorithm. Talatahari et al. [7] developed a material generation algorithm and implemented it for the optimum design of engineering problems, including ten bar truss optimization problem. Yu et al. [8] introduced interior point trust region method to solve the truss structural frequency optimization problems. Lamberti and Pappalettere [9] solved truss structure weight minimization problems using linearization error sequential linear programming. Kaveh and Zolghadr [1] solved truss structures under frequency constraints using the charged system search algorithm and its enhanced version. Eskandar et al. [10] solved the ten bar truss weight optimization problem with displacement and stress constraints using water cycle algorithm. Kaveh and Hassani [11] developed the energy formulation of force method and simultaneously performed optimization of truss structures. Rao et al. [12] solved the truss optimization problem by applying the Rao algorithms, Quasi oppositional Rao algorithms and self-adaptive multi-population Rao algorithms.

Turky and Abdullah [13] introduced a multi-population harmony search algorithm to solve dynamic optimization problems (DOP). In the proposed algorithm, the population of solutions was split into a number of sub-populations for better exploration and exploitation. The proposed algorithm's performance was examined on the moving peak benchmark problems. Feng et al. [14] presented chaos optimization algorithm. The chaotic sequences generated by sixteen chaotic maps were analyzed. The proposed algorithm was applied to test functions to demonstrate its high efficiency and convergence rate. Rao [15] introduced algorithm-specific parameter less Rao algorithms to solve the optimization problems related to different fields. From the literature review, it is observed that the algorithm's performance can be improved by integrating concepts like multi-population, elitism and chaos theory with the basic metaheuristic algorithm. So in the present paper, the self-adaptive multi-population elitist (SAMPE) Rao algorithms and chaotic Rao algorithms are utilized to solve the ten bar truss optimization problem.

The remainder of the paper has the following structure: Sect. 2 describes the Rao, SAMPE Rao and chaotic Rao algorithms. Section 3 describes the two examples of ten bar truss optimization problem. Section 4 discusses the results obtained after

applying the proposed algorithms to the problems. Section 5 presents the conclusions of the present paper.

## 2 Rao, SAMPE Rao and Chaotic Rao Algorithms

### 2.1 Rao Algorithms

Rao algorithms are recently developed algorithm-specific parameter less optimization algorithms [15]. Rao algorithms use the best and the worst candidate solutions of the population to find an optimal solution during the search process. Rao2 and Rao3 algorithms also use the random interaction between the candidates during the search process. In Rao algorithms, the random population is generated initially, and the value of variables is updated using the following equations.

$$x'_{vn,cn,in} = x_{vn,cn,in} + r_{1,vn,in}(x_{vn,best,in} - x_{vn,worst,in}) \quad (1)$$

$$x'_{vn,cn,in} = x_{vn,cn,in} + r_{1,vn,in}(x_{vn,best,in} - x_{vn,worst,in}) \\ + r_{2,vn,in}(|x_{vn,c1,in} \text{ OR } x_{vn,c2,in}| - |x_{vn,c2,in} \text{ OR } x_{vn,c1,in}|) \quad (2)$$

$$x'_{vn,cn,in} = x_{vn,cn,in} + r_{1,vn,in}(x_{vn,best,in} - |x_{vn,worst,in}|) \\ + r_{2,vn,in}(|x_{vn,c1,in} \text{ OR } x_{vn,c2,in}| - (x_{vn,c2,in} \text{ OR } x_{vn,c1,in})) \quad (3)$$

where  $x_{vn,cn,in}$  represents the value of variable 'vn' for candidate number 'cn' for iteration number 'in'.  $x'_{vn,cn,in}$  is the updated value of  $x_{vn,cn,in}$ .  $r_{1,vn,in}$  and  $r_{2,vn,in}$  are the random numbers between 0 and 1. The random interaction is done between candidate number 'c1' and 'c2'

### 2.2 Self-Adaptive Multi Population Elitist (SAMPE) Rao Algorithms

SAMPE Rao algorithms include the concept of multi-population and elitism to improve the rate of exploration and exploitation of the search mechanism. In SAMPE Rao algorithms, first the elite size (ES), number of variables and the population size ( $m$ ) are initialized. In SAMPE Rao algorithms, the sub-populations are formulated from the whole population. The subgroups are formed according to the quality of the solution. Then, the 'ES' number of worst solutions from the inferior group is replaced with the best solutions of the superior group. Then, the equations of Rao algorithms are used to modify the candidate solutions in each sub-population. Then,

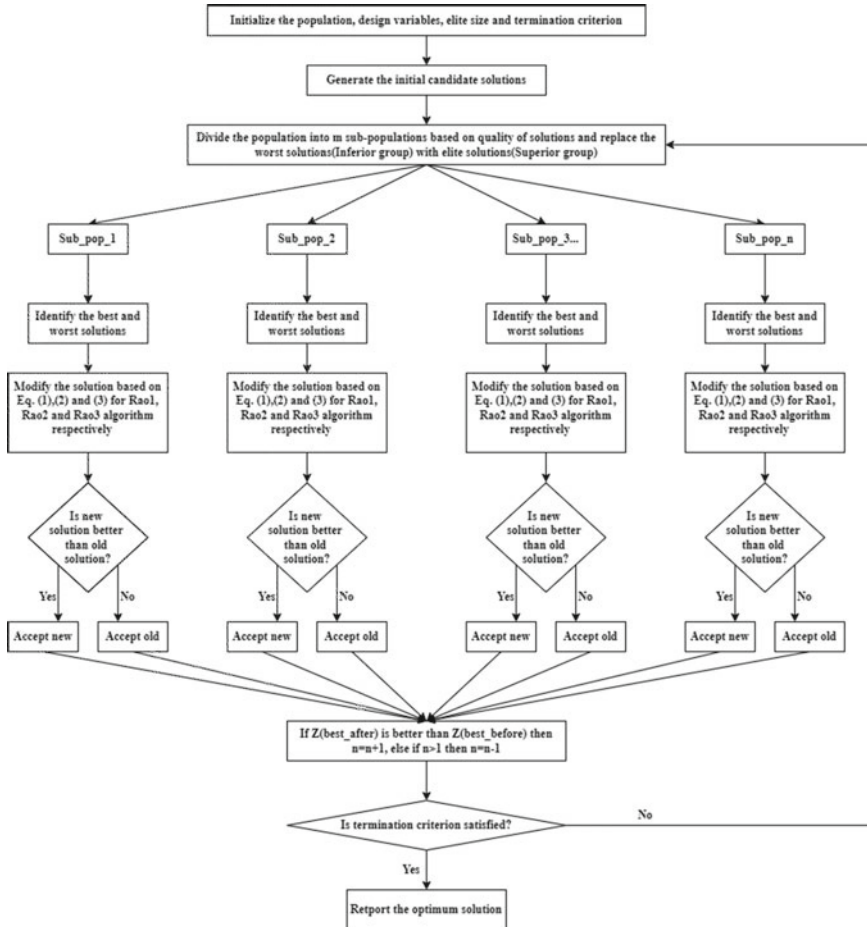


Fig. 1 Flowchart of the SAMPE Rao algorithms

all the sub-populations are merged in a single population. If the current best solution is better than the previous best solution, then the number of sub-population is increased by one for exploration; otherwise, it is decreased by one for exploitation. Figure 1 shows the flowchart of SAMPE Rao algorithms.

### 2.3 Chaotic Rao Algorithms

The chaotic Rao algorithms integrate the Rao algorithms and the chaos theory. In these algorithms, the random numbers used in the equations of Rao algorithms are replaced with the chaotic numbers. The chaotic numbers are generated using the

mathematical equation of the chaotic map. The researchers have developed different chaotic maps in the past to generate chaotic numbers. Some of the chaotic maps are logistic map, Kent map, Bernoulli shift map, sine map, circle map, Chebyshev map, Gaussian map, etc. The chaotic Rao algorithms help to find a global optimal solution without getting trapped at local optima. The performance of the algorithms is tested using the chaotic numbers generated by different chaotic maps. The algorithms give better results when the Chebyshev map is used to generate the chaotic numbers. The Eq. (4) is used to generate chaotic number when the Chebyshev map is used. Figure 2 shows the flowchart of chaotic Rao algorithms

$$x_{i+1} = |\cos(k \cos^{-1}(x_i))|, \quad x_i \in [0, 1], \quad k > 1 \tag{4}$$

where  $x_{i+1}$  and  $x_i$  are  $(i + 1)$ th and  $i$ th term of a chaotic sequence, respectively.

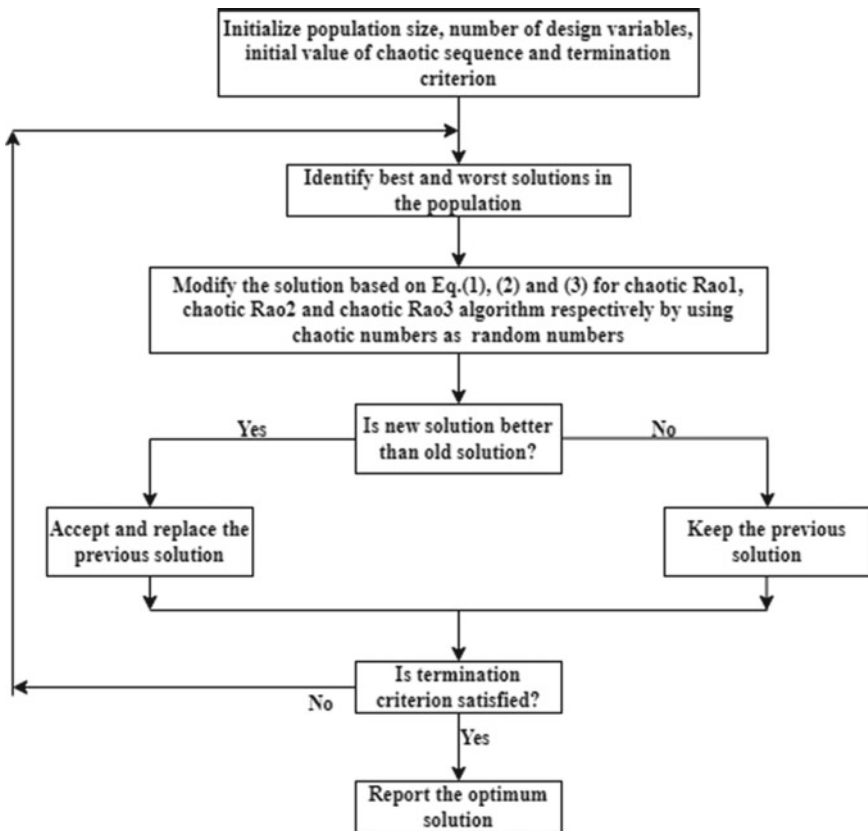


Fig. 2 Flowchart of chaotic Rao algorithms

### 3 Optimization Problem of Planar Ten Bar Truss

#### 3.1 Ten Bar Truss Optimization Problem-1

The weight minimization problem of ten bar truss with frequency constraints was first addressed by Grandhi and Venkayya [16]. In this problem, the cross-sectional area of bars is considered as design variables. The truss material has Young's modulus and density equal to 68.95 GPa and 2767.99 kg/m<sup>3</sup>, respectively. Different researches had used different values of Young's modulus in the past for this problem. In this paper, the value of Young's modulus is considered same as it was considered by Grandhi and Venkayya [16]. At each free end of the truss (at node number 2, 3, 4 and 5), a mass of 453.6 kg is attached. The value of natural frequency is calculated using the global stiffness and the global mass matrix. The consistent mass matrix is used to find accurate results of the natural frequency. Figure 3 shows the schematic diagram of ten bar truss for problem-1.

The mathematical model of the ten bar truss optimization problem-1: Design variables:

$$\bar{x} = [A_1, A_2, \dots, A_{10}]$$

Objective function:

Minimize,

$$f(\bar{x}) = \rho \sum_{i=1}^{10} L_i(x_i) A_i \quad (5)$$

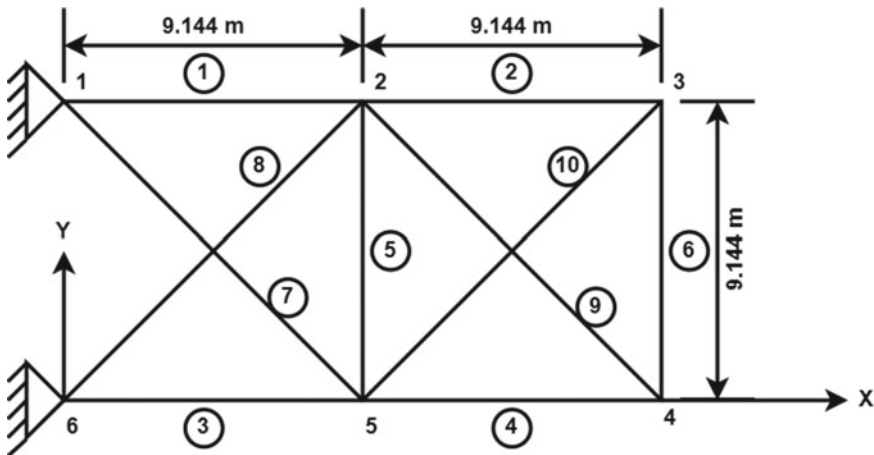


Fig. 3 Ten bar truss for problem-1

Design constraints:

$$C_1(\bar{x}) = \omega_1(\bar{x}) - 7 \geq 0 \quad (6)$$

$$C_2(\bar{x}) = \omega_2(\bar{x}) - 15 \geq 0 \quad (7)$$

$$C_3(\bar{x}) = \omega_3(\bar{x}) - 20 \geq 0 \quad (8)$$

$$6.45 \times 10^{-5} \leq A_i \leq 5 \times 10^{-3} \quad (9)$$

where,

$$\rho = \text{Density} = 2767.99 \text{kg/m}^3,$$

$$L_i(x_i) = \text{Length of the } i\text{th bar (m), } i = 1, 2, \dots, 10$$

$$\omega_1, \omega_2 \text{ and } \omega_3 = \text{First three natural frequencies of the truss structure (Hz),}$$

$$A_i = \text{Cross - sectional area of } i\text{th truss member (m}^2\text{), } i = 1, 2, \dots, 10$$

### 3.2 Ten bar Truss Optimization Problem-2

This problem minimizes the weight of the ten bar truss subjected to constraints associated with the nodal displacement and the stress in the truss members. In this problem, the cross-sectional area of the truss members is the design variables. The truss is made of the material with Young's modulus equal to  $10^7$  psi and density equal to  $0.1 \text{ lb/in}^3$ . The maximum allowable displacement at the free nodes is  $\pm 2$ , in and the maximum allowable stress in the truss members is  $\pm 25$  ksi. Load  $P_1 = 10^5 \text{ lb}$  and  $P_2 = 0 \text{ lb}$  are acting at the free nodes as shown in Fig. 4.

The mathematical model of the ten bar truss optimization problem-2: Design variables:

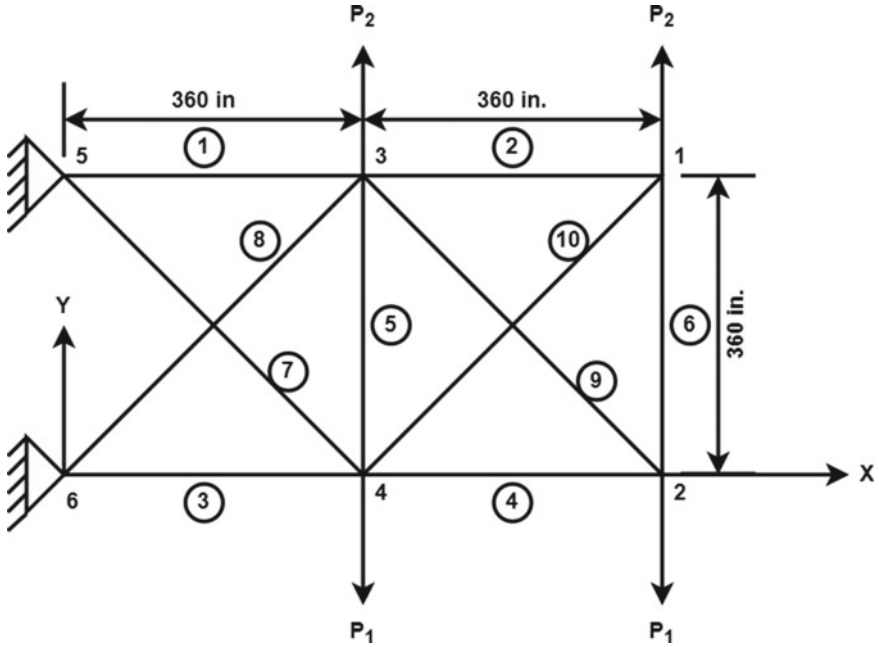
$$\bar{x} = [A_1, A_2, \dots, A_{10}]$$

Objective function:

Minimize,

$$f(\bar{x}) = \rho \sum_{i=1}^{10} L_i(x_i) A_i \quad (10)$$

Design constraints:



**Fig. 4** Ten bar truss for problem-2

$$-2 \leq u_{xi} \leq 2 \quad (11)$$

$$-2 \leq u_{yi} \leq 2 \quad (12)$$

$$-25 \leq \sigma_j \leq 25 \quad (13)$$

$$0.1 \leq A_j \leq 35 \quad (14)$$

where

$\rho = \text{Density} = 0.11\text{lb/in}^3$ ,

$L_i(x_i) = \text{Length of the } i\text{th bar (in), } i = 1, 2, \dots, 10$

$u_{xi} = \text{Displacement in x direction at } i\text{th node (in), } i = 1, 2, 3, 4$

$u_{yi} = \text{Displacement in y direction at } i\text{th node (in), } i = 1, 2, 3, 4$

$\sigma_j = \text{Induced stress in } j\text{th truss member (ksi), } j = 1, 2, \dots, 10$

$A_j = \text{Cross - sectional area of } j\text{th truss member (in}^2\text{), } j = 1, 2, \dots, 10$

## 4 Results and Discussion

The optimization results are obtained with the R2019a version of the MATLAB tool. The laptop with the 1.80-GHz Intel Core i7-8550U processor and 8 GB RAM is utilized for computation. The ten bar optimization problem is solved using Rao, SAMPE Rao and chaotic Rao algorithms for 25 times. Various combinations of population size with elite size and initial value of chaotic sequence are tested for SAMPE and chaotic Rao algorithms, respectively, and the combination which gives the best result for different algorithms is also mentioned for both problems. The optimal results achieved using Rao, SAMPE Rao, chaotic Rao algorithms and other advanced optimization algorithms are compared. The bold numbers highlight the improvement in the results from Rao algorithms to modified Rao algorithms.

### 4.1 Ten Bar Truss Optimization Problem-1

This problem is solved using the presented algorithms with the number of maximum function evaluations equal to 50,000. Table 1 compares the optimal design of ten bar truss obtained using presented algorithms, interior point trust region method (IPTRM), sequential linear programming (SLP), teaching learning-based optimization (TLBO), enhanced charged system search (ECSS) and material generation algorithm (MGA). Table 2 compares the statistical results of the presented algorithms. The optimal results attained using the presented algorithms are better than the same obtained using other algorithms. Figure 5 represents the convergence plot of the Rao, SAMPE Rao and chaotic Rao algorithms for the ten bar truss optimization problem. SAMPE Rao3 algorithm reaches first to its optimal value for this problem.

### 4.2 Ten Bar Truss Optimization Problem-2

This problem is solved by applying the presented algorithms with the number of maximum function evaluations equal to 50,000. Table 3 compares the optimal design of ten bar truss obtained using presented algorithms, ant colony optimization (ACO), particle swarm optimization (PSO), hybrid genetic algorithm and particle swarm optimization (HGAPSO), water cycle algorithm (WCA), Rao algorithms, quasi-oppositional (QO) Rao algorithms and self-adaptive multi-population (SAMP) Rao algorithms. Table 4 compares the statistical results attained using the SAMPE and chaotic Rao algorithms. The optimal results achieved using the presented algorithms are better than the same achieved using other algorithms. Figure 6 represents the convergence plot of the SAMPE Rao and chaotic Rao algorithms for the ten bar truss optimization problem. chaotic Rao2 algorithm reaches first to its optimal value for this problem.

**Table 1** Comparison of optimal results for ten bar problem-1 using different algorithms

Algorithm	$f_{min}$	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$	$A_6$	$A_7$	$A_8$	$A_9$	$A_{10}$	$C_1$	$C_2$	$C_3$
IPTRM <sup>a</sup>	544.7	36.38	12.941	35.764	18.314	3.002	5.433	20.989	24.14	9.753	18.102	1.000E-03	3.077E+00	2.500E-02
SLP <sup>a</sup>	534.57	35.148	13.169	37.69	19.556	1.087	4.844	18.314	27.415	12.562	12.106	3.000E-03	1.543E+00	1.540E-01
TLBO <sup>a</sup>	530.76	35.494	14.777	36.203	15.387	0.6451	4.5896	23.211	24.561	12.482	12.324	0.000E+00	1.201E+00	0.000E+00
ECSS <sup>a,b</sup>	529.25	39.569	16.74	34.361	12.994	0.645	4.802	26.182	21.26	11.766	11.392	-1.438E-01	1.115E+00	-2.322E-01
MGA <sup>a,b</sup>	529.1204	36.76416	16.29897	37.94378	16.51087	0.659	4.57489	22.94023	22.63185	10.87892	11.53643	-1.263E-01	1.390E+00	-1.757E-01
Rao1	530.0966	42.480315	6.595627	35.6382	19.92667	1.40975	5.768395	15.05489	28.39336	17.339118	8.239324	1.160E-04	1.294E-02	7.834E-04
Rao2	530.0938	42.459438	6.685081	35.731579	19.82831	1.42142	5.747557	15.025042	28.44203	17.136444	8.383884	2.432E-05	6.012E-02	2.626E-04
Rao3	530.0896	42.386852	6.716022	35.909957	19.7412	1.332839	5.747599	14.87662	28.76973	17.091302	8.276102	3.305E-05	9.102E-03	1.036E-04
SAMPE Rao1	530.0717	42.512825	6.638253	35.771085	19.82477	1.376879	5.698903	14.97328	28.6608	17.212648	8.170349	1.316E-05	1.016E-02	5.850E-04
SAMPE Rao2	530.0751	42.712725	6.603847	35.681113	19.8947	1.422724	5.732315	14.884304	28.47374	17.27057	8.230496	6.679E-06	1.058E-02	2.958E-04
SAMPE Rao3	530.0774	42.516889	6.557441	36.00458	19.72067	1.415428	5.720058	15.049094	28.50076	17.207818	8.181558	1.867E-05	4.381E-03	1.808E-04
Chaotic Rao1	530.0779	42.277734	6.66225	35.779458	19.72491	1.373387	5.716021	14.936021	28.79303	17.276601	8.21746	2.052E-06	1.135E-02	2.971E-04
Chaotic Rao2	530.0896	42.776385	6.595907	35.873518	19.72962	1.405614	5.750094	14.888098	28.57553	17.136128	8.204217	6.317E-06	1.587E-03	6.838E-04
Chaotic Rao3	530.0770	42.586354	6.597214	35.723756	19.84644	1.427229	5.719932	15.013244	28.44623	17.193726	8.310047	1.672E-05	2.130E-02	2.870E-04

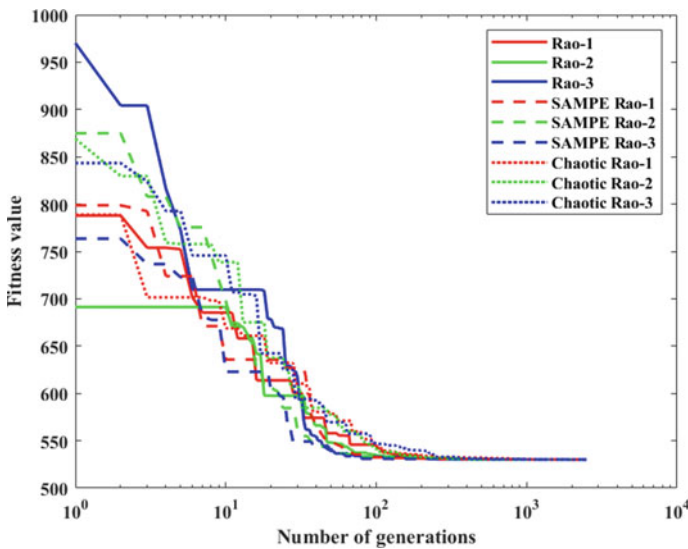
<sup>a</sup>The results are taken from [7]

<sup>b</sup>Infeasible solution due to violation of constraints

**Table 2** Statistical result comparison for ten bar truss problem-1

Algorithm	<i>B</i>	<i>M</i>	<i>W</i>	<i>SD</i>	<i>MFE</i>	<i>NP, ES/CS<sub>1</sub></i>
Rao1	530.0966	530.1672	530.4509	9.091E−02	42,205	20
Rao2	530.0938	530.7118	539.6865	1.887E + 00	44,224	20
Rao3	530.0896	530.4269	533.9654	7.594E−01	42,700	20
SAMPE Rao1	530.0717	530.3919	533.8421	7.495E−01	43,449	20, 2
SAMPE Rao2	530.0751	530.4881	531.3110	3.501E−01	43,120	20, 2
SAMPE Rao3	530.0774	530.5175	531.5239	3.485E−01	40,208	20, 2
Chaotic Rao1	530.0779	530.3403	533.8971	7.697E−01	44,322	20, 0.3
Chaotic Rao2	530.0896	530.4039	531.0919	3.590E−01	43,332	20, 0.3
Chaotic Rao3	530.0770	531.2531	540.5291	2.788E + 00	46,970	20, 0.2

*B* Best solution, *M* Mean solution, *W* Worst solution, *SD* Standard deviation, *MFE* Mean function evaluations, *NP* Population size, *ES* Elite size, *CS<sub>1</sub>* Initial value of chaotic sequence



**Fig. 5** Convergence plot for the ten bar truss problem-1

## 5 Conclusions

In this paper, two structural optimization problems of ten bar truss are solved using the Rao algorithms, self-adaptive multi-population elitist (SAMPE) Rao algorithms and chaotic Rao algorithms. The optimal design of the ten bar truss attained using the presented algorithms is compared with the those obtained using other optimization algorithms to show the effectiveness of the presented algorithms. The statistical results of Rao algorithms, SAMPE Rao algorithms and chaotic Rao algorithms are

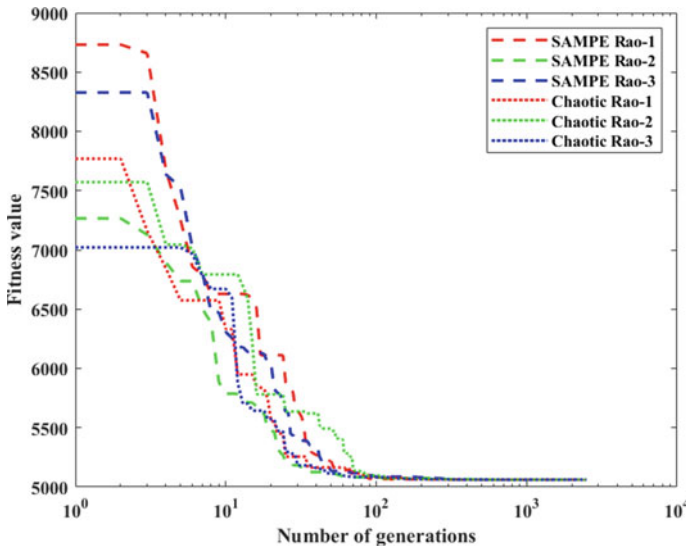
**Table 3** Comparison of optimal design for ten bar problem-2 using different algorithms

Algorithm	$f_{\min}$	$A_1$	$A_2$	$A_3$	$A_4$	$A_5$	$A_6$	$A_7$	$A_8$	$A_9$	$A_{10}$
ACO <sup>a</sup>	5095.46	30.86	0.1	23.55	0.22	15.01	0.1	7.63	21.65	21.32	0.1
HGAPSO <sup>a</sup>	5061.4	30.63	0.1	23.06	15.01	0.1	0.59	7.49	21.1	21.56	0.1
PSO <sup>a</sup>	5529.5	33.46	0.11	23.17	15.47	3.64	0.11	8.32	23.34	23.01	0.19
WCA <sup>a</sup>	5061.02	30.53	0.1	23.05	15.03	0.1	0.56	7.48	21.12	21.63	0.1
Rao1 <sup>a</sup>	5060.9568	30.5227	0.1002	23.2368	15.1605	0.1	0.5661	7.4616	21.0822	21.487	0.1
Rao2 <sup>a</sup>	5060.9248	30.4316	0.1003	23.187	15.2439	0.1	0.5556	7.4588	21.0671	21.5524	0.1
Rao3 <sup>a</sup>	5060.914809	30.494	0.1	23.1769	15.1519	0.1001	0.5565	7.4655	21.0929	21.5473	0.1
SAMP Rao1 <sup>a</sup>	5060.9179	30.4397	0.1	23.2744	15.2244	0.1	0.5673	7.4478	21.0285	21.5401	0.1
SAMP Rao2 <sup>a</sup>	5060.8901	30.5175	0.1	23.2595	15.2282	0.1001	0.5422	7.4495	21.0131	21.5238	0.1
SAMP Rao3 <sup>a</sup>	5060.9056	30.6059	0.1	23.1606	15.2676	0.1	0.543	7.4659	21.0492	21.4506	0.1
QO-Rao1 <sup>a</sup>	5060.9274	30.4877	0.1002	23.1442	15.3299	0.1	0.5624	7.4581	21.0228	21.5225	0.1
QO-Rao2 <sup>a</sup>	5060.9113	30.6113	0.1	23.2193	15.1663	0.1	0.5696	7.458	21.0216	21.4938	0.1
QO-Rao3 <sup>a</sup>	5060.9136	30.5902	0.1001	23.1012	15.1722	0.1	0.556	7.4675	21.0354	21.5743	0.1
SAMPE Rao1	5060.8908	30.576134	0.100012	23.172501	15.19647	0.1	0.545689	7.458065	21.00616	21.56222	0.1
SAMPE Rao2	5060.8900	30.563172	0.1	23.177081	15.26809	0.1	0.552216	7.453648	20.97761	21.54585	0.1
SAMPE Rao3	5060.8840	30.551849	0.1	23.119761	15.28698	0.1	0.559175	7.460543	21.00636	21.54034	0.1
Chaotic Rao1	5060.9000	30.635388	0.1	23.234186	15.21234	0.1	0.534306	7.457509	21.01874	21.4617	0.1
Chaotic Rao2	5060.8765	30.51544	0.1	23.1954	15.26967	0.100011	0.554081	7.452355	20.99788	21.54496	0.1
Chaotic Rao3	5060.9044	30.508544	0.10003	23.189486	15.27114	0.100006	0.550928	7.452335	20.99723	21.5564	0.1

<sup>a</sup>The results are taken from [12]

**Table 4** Statistical result comparison for ten bar truss problem-2

Algorithm	<i>B</i>	<i>M</i>	<i>W</i>	SD	MFE	NP, ES/CS1
SAMPE Rao1	5060.8908	5096.4800	5524.7482	9.953E + 01	40,010.0	20, 2
SAMPE Rao2	5060.8900	5089.3144	5409.1376	7.396E + 01	43,182.0	20, 2
SAMPE Rao3	5060.8840	5067.5086	5087.1779	9.239E + 00	40,679.0	20, 2
Chaotic Rao1	5060.9000	5083.2757	5418.7143	7.041E + 01	44,488.0	20, 0.2
Chaotic Rao2	5060.8765	5137.9980	6341.4127	2.593E + 02	44,116.0	20, 0.6
Chaotic Rao3	5060.9044	5104.0287	5269.9448	6.638E + 01	42,775.0	20, 0.2



**Fig. 6** Convergence plot for the ten bar truss problem-2

also compared. The presented algorithms give better optimal results than the other optimization algorithms for both optimization problems considered.

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# Crack Identification in Pipe Using Improved Artificial Neural Network



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## 1 Introduction

Recently, many new methods have been developed in order to detect the damage of different structures such as beam, pipe, bridge and plates structures. However, the crack identification based on new method, e.g. ANN-PSO, TLBO-PSO-ANN, XFEM, XIGA, IGA and cuckoo search algorithm, etc., has become a very interesting domain and has received significant attention where many researchers work on it. In fact, Gillich et al. [1] studied the free vibration of clamped-free beam and used a new power method to detect the damage on multi modal analysis by taking into account different temperature conditions. The crack identification in beam with multiple cracks has been also studied by Gillich et al. [2], where a simplified method based on the frequency shifts has been used and it has been concluded that when the vibration

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modes were sufficient, the eigenfrequencies were capable of indicating the depth and position of damage. Seguini et al. [3] used the ANN-PSO method to identify also the multiple cracks on two different beams, where the efficiency of the developed models has been proved by making comparison between experimental and numerical results where the percentage of error was very small.

Zhou et al. [4, 5] used the transmissibility and the hierarchical clustering analysis to detect the damage in the structures. In another research, Khatir et al. [6] used the neural network based on the hybrid TLBO and partial swarm optimization (PSO) in order to identify the damage in steel beams. Moreover, several works have been made to investigate the energy approach using on the machine learning concepts in Refs. [7, 8]. Tran et al. [9] used the cuckoo search algorithm combined with neural artificial network (ANN) to detect the damage in bridge and beam-like structures. A novel machine learning method has been also used by the same authors in Ref. [10] to identify the damage in structures by using vectorized data. Different other new methods have been also used to identify the crack in plates using improved ANN technique for solving crack identification based on XFEM, XIGA, PSO and Jaya algorithm [11, 12]. However, the influence of the depth and position of cracks on the response of the pipe has been studied by different researchers [13–17]. In fact, Seguini et al. [14, 15] used the ANN-PSO method in order to identify the crack in the pipes, where numerical and experimental modal analysis have been done and the measured frequencies of cracked and uncracked pipe have been deduced for each depth crack. The obtained results reveal the importance and the efficiency of the ANN-PSO method. The present study focuses on the numerical modal analysis of the cracked pipe by using finite element analysis combined with GA-ANN. However, a new approach has been used in order to identify the crack in the pipe, where many simulations have been generated by using MATLAB software until the convergence is reached. From this analysis, the values of frequencies of three modes shape have been deduced for each depth crack. The noticeable in the present work is that GA-ANN allows us to improve the results and obtain an exact solution in short times instead of inverse analysis.

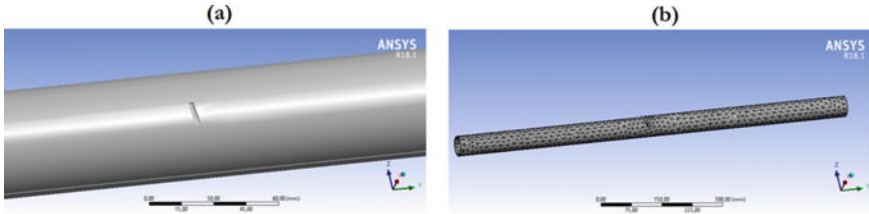
## 2 Finite Element Analysis

In this section, 3D finite element model of pipe has been modelled by using ANSYS software, where the mechanical and geometrical properties are presented in Table 1 [14]. A multiples cracks depth has been created in the middle, on the left and right side of the pipe. The cracks have been extended from 2 to 16 mm, and two scenarios have been studied as shown in Figs. 2 and 3. The frequencies of scenarios 1 and 2 are listed in Table 4 (Appendix). The FEM including mesh type is presented in Fig. 1.

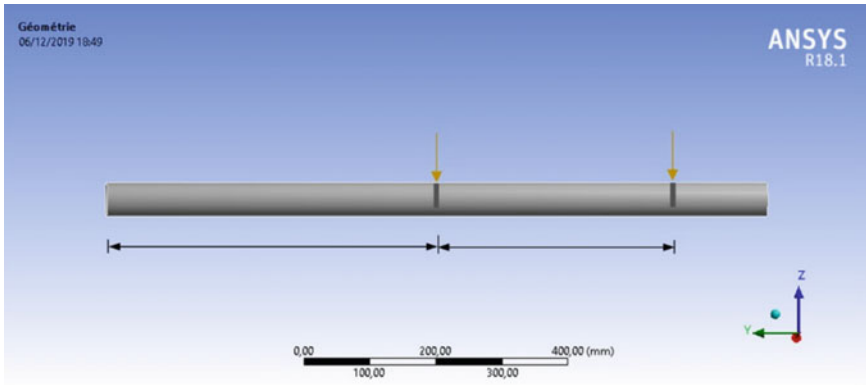
However, in order to demonstrate the important effect of multiple cracks on the pipe response, a crack with different depths has been created in the middle and right of the pipe (scenario 1), and another double crack has been created on the middle and left side of the pipe (scenario 2). The natural frequencies of the third modes have

**Table 1** Mechanical properties of the pipe [14]

Item	Value
Length $L_p$ (mm)	1000
Diameter $D_p$ (mm)	50
Density $\rho$ (Kg/m <sup>3</sup> )	7850
Poisson ratio $\nu_p$ ( $l$ )	0.3
Young modulus $E_p$ (MPa)	61950



**Fig. 1** Cracked pipe: (a) Finite Element Model and (b) meshed pipe



**Fig. 2** Pipeline with double notched (scenario 1): middle crack and right crack

been determined for different depths of crack and listed on Table 4 of the Appendix, where some examples have been chosen and illustrated as shown on Figs. 4 and 5. From Table 4, it can be seen that the values of the natural frequencies decrease for the three mode and by comparing the results obtained from the two scenarios, it can be deduced that there is a small difference between the frequencies of the three mode shapes.

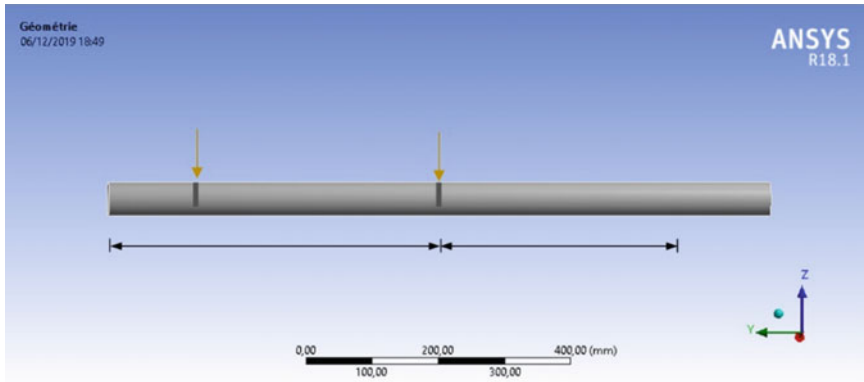


Fig. 3 Pipeline with double notched (scenario 2): middle crack and left crack

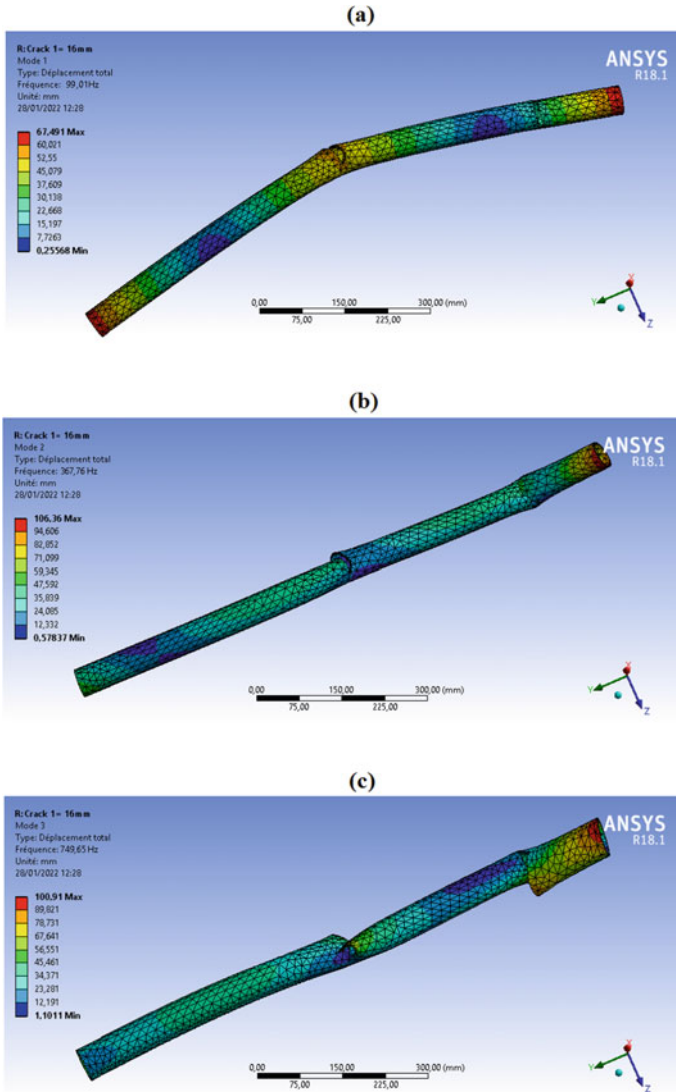
### 3 Results and Discussion

GA is an optimization method based on natural selection and on the class of evolutionary algorithms. The objective of using GA is to find the best solution after combining with ANN. The purpose is to find the best weight and bias during the training process. Through series of damage location tests, the following genetic parameters were chosen precisely in order to obtain an accuracy result: the number of generations of 500, population size of 200. This technique is implemented in MATLAB.

In the first scenario, the regressions of ANN of each hidden layer size ( $n = 4, 6$  and  $8$ ) are presented in Fig. 6 and the predicted results are resumed in Table 2. It can be deduced that GA provides accurate results for  $n = 6$  based on the convergence study and regression value compared with others. Based on the obtained results, we can resume that GA can predict the crack depth 5.5 and 12.5 mm accurately for different hidden layer sizes, where the results are represented by bar graph (Fig. 7). In the second scenario, the same number of hidden layers has been adopted. The regression of GA is presented in Fig. 8, where the obtained results are presented in Table 3. However, the best convergence is found for  $n = 4$  compared with others. From the obtained results, we can deduced that GA can predict the crack depth 7.5 and 14.5 mm accurately for different hidden layer sizes, where the results are also represented by bar graph as shown in Fig. 9.

### 4 Conclusion

Nowadays, great complex problems have been solved by using different numerical methods. However, in our study, GA-ANN was utilized for identifying the damage of multiple cracks on the pipe. However, numerical analysis has been



**Fig. 4** Natural frequencies for different modes of double notched pipe (scenario 1): (a) mode 1, (b) mode 2 and (c) mode 3 of pipe with cracks of 16 mm

done and two scenarios have been studied. The values of the frequencies of the first three modes have been deduced for each crack depth and position, where the convergence of the results has been proved through the proposed method.

From this work, it has been noted that interesting results have been obtained when a multiple-crack scenario has been considered, and by adopting the GA-ANN method, the accuracy of the results has been proven.