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TRUSS OPTIMIZATION WITH NATURAL FREQUENCY CONSTRAINTS USING A DOLPHIN ECHOLOCATION ALGORITHM

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ABSTRACT

Dynamic response of a structure is a remarkable characteristic which can be optimized (controlled) by imposing constraints on natural frequencies. But it is mentionable that size and shape optimization of trusses with multiple frequency constraints is a very non-linear and non-convex problem that may be converged to local optima when using meta-heuristic algorithms. To concur this problem, researchers have developed hybrid meta-heuristic algorithms.

In this paper recently introduced dolphin echolocation algorithm is applied for optimum design of truss structures with frequency constraints. Four numerical examples are considered to demonstrate the efficiency of the algorithm in comparison to hybrid meta-heuristic algorithms.

Keywords:

1. INTRODUCTION

Weight optimization of structures with frequency constraints is an important problem especially for structures that are exposed to wind, hurricanes or violent earthquake. In fact, by imposing constraints on natural frequencies, one can reduce the domain of vibration and prevent the resonance phenomenon in dynamic response of structures [1]. But there are two common problems in frequency optimization. One problem is switching of vibration modes due to structural size and shape modifications that causes convergence difficulties in optimization. Another problem is the fact that some structures exhibit repeated eigenvalues even though the initial design did not have any [2]. Some optimization methods have been employed for optimum design of structures subjected to multiple frequency constraints. One of the first papers contributed to this field was by Bellagamba and Yang [3]. In this paper, a constrained parameter

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optimization technique using Gauss method was presented. Yang et al [4] developed an evolutionary method of gradually omitting inefficient material to be replaced with new material for structural topology optimization with frequency constraints. McGee and Phan [5] introduced an efficient optimality criteria (OC) method taking advantage of Kuhn-Tucker condition. Sedaghati [6] proposed a new approach using combined mathematical programming based on the Sequential Quadratic Programming (SQP) technique, and the finite element technique based on the Integrated Force Method. Lin et al. [7] utilized a bi-factor algorithm based on the Kuhn–Tucker criteria. All these methods were time consuming and hard to apply. After that meta-heuristic algorithms have been introduced, they have been taken into consideration for being applied to structural optimization with frequency constraints. Gomes [8] has been one of the pioneers in this field. He used standard particle swarm algorithm for simultaneous layout and size optimization of truss structures. Lingyun et al. [9] presented an enhanced genetic algorithm called NGHA (niche genetic algorithm). This hybrid algorithm, developed by combining simplex search and genetic algorithm, followed a nature based scheme of niche. Gholizadeh et al. [1] and Salajegheh et al. [10] used Genetic Algorithm (GA) and neural network (NN) togethere to optimize structures subjected to multiple natural frequency constraints. Kaveh and Zolghadr [11] employed the Charged System Search (CSS) algorithm and its enhanced form to solve the problem. Also Kaveh and Zolghadr [12] proposed a hybridized algorithm, CSS–BBBC, with trap recognition capability for weight optimization of trusses on layout and size optimization. Furthermore, Kaveh and Zolghadr [13] presented a new hybrid meta-heuristic algorithm called Democratic PSO for truss layout and size optimization with frequency constraints. Kaveh and Javadi [14] utilized harmony search and a ray optimizer for enhancing the particle swarm optimization algorithm (HRPSO). Kaveh and Mahdavi [15] used a hybridized BB-BC/Quasi-Newton algorithm, and Kaveh and Mahdavi [16] utilized Colliding Bodies Optimization (CBO) for truss optimization with multiple frequency cobstraints.

As mentioned, so far different methods have been employed to truss mass optimization with frequency constraints, considering that recently hybrid meta-heuristic algorithms have been taken into account more. This is because of the problem that such an algorithm with high exploitation is needed to explore a rather highly non-linear and non-convex search space with several local optima. Thus hybrid meta-heuristic algorithms have been known better choice for this kind of optimization problems.

Dolphin echolocation algorithm, recently developed optimization method by Kaveh and Farhoudi [17], is going to be used in this paper. Dolphin echolocation algorithm is the first algorithm using CF index. CF is defined as convergence factor in the paper presented by Kaveh and Farhoudi [18]. With convergence factor (CF), we can control somewhat the exploration and explotation of an algorithm. In this paper the convergence rate of DEO (Dolphin echolocation algorithm) is investigated in comparison with hybrid meta-heuristic algorithms in structural optimization with frequency constraints.

After this introduction, Section 2 presents the dolphin's echolocation in nature. Section 3 introduces dolphin echolocation algorithm, Section 4 states problem formulation, Section 5 presents numerical examples. The last section is devoted to concluding remarks indicating the capabilities of the DE in comparison to some other meta-heuristic algorithms.

2. DOLPHIN ECHOLOCATION IN NATURE

Dolphin echolocation mimics strategies used by dolphins for their hunting process. Dolphins produce a kind of voice called sonar to locate the target, doing this dolphin change sonar to modify the target and its location. Dolphin echolocation is depicted in Fig. 1. This fact is mimicked here as the main feature of the new optimization method [17].

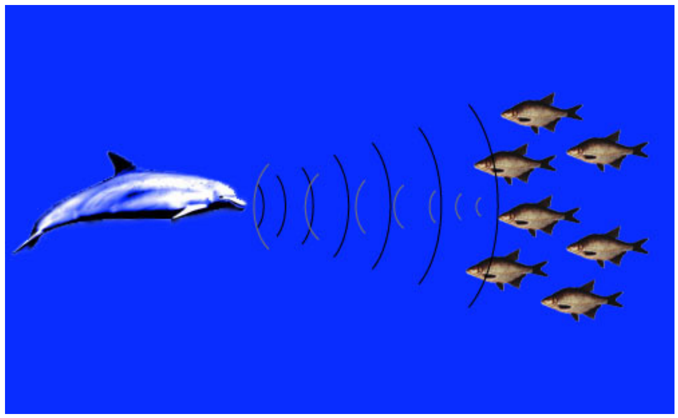


Figure 1. A real dolphin catching its prey

3. INTRODUCTION TO DOLPHIN ECHOLOCATION

Regarding an optimization problem, it can be understood that echolocation is similar to optimization in some aspects; the process of foraging preys using echolocation in dolphins is similar to finding the optimum answer of a problem.

Dolphins initially search all around the search space to find the prey. As soon as a dolphin approaches the target, the animal restricts its search, and incrementally increases its clicks in order to concentrate on the location.

The method simulates dolphin echolocation by limiting its exploration proportional to the distance from the target. For making the relationship much clear, consider an optimization problem. Two stages can be identified: in the first stage the algorithm explores all around the search space to perform a global search, therefore it should look for unexplored regions. This task is carried out by exploring some random locations in the search space, and in the second stage it concentrates on investigation around better results achieved from the previous stage. These are obvious inherent characteristics of all meta-heuristic algorithms. An efficient method is presented in Ref. [18] for controlling the value of the randomly created answers in order to set the ratio of the results to be achieved in phase 1 to phase 2.

By applying Dolphin Echolocation (DE) algorithm, the user would be able to change the ratio of answers produced in phase 1 to the answers produces in phase 2 according to a predefined curve. In other words, global search, changes to a local one gradually in a user defined style.

The user defines a curve on which the optimization convergence should be performed, and then the algorithm sets its parameters in order to be able to follow the curve. The method works with the likelihood of occurrence of the best answer in comparison to the others. In other words, for each variable there are different alternatives in the feasible region, in each loop the algorithm defines the possibility of choosing the best so far achieved alternative according to the user determined convergence curve. By using this curve, the convergence criterion is dictated to the algorithm, and then the convergence of the algorithm becomes less parameter dependent. The curve can be any smooth ascending curve but there are some recommendations for it.

Previously, it has been shown that there is a unified method for parameter selection in meta-heuristics [18]. In the latter paper, an index called the convergence factor was presented. A *Convergence Factor* (*CF*) is defined as the average possibility of the elitist answer.

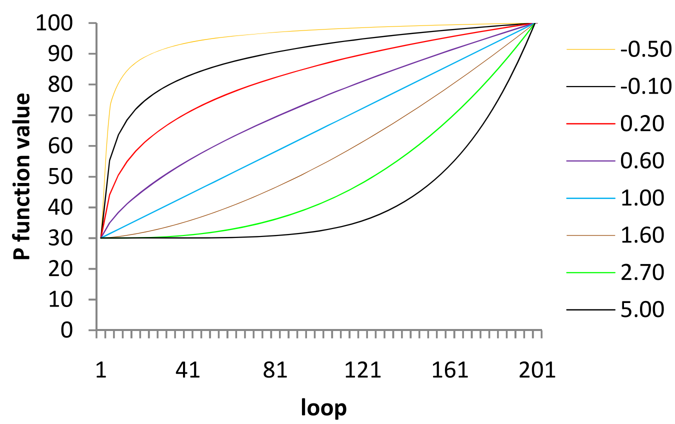


Figure 2. Sample convergence curves, applying Eq. (1) for different values of power [1].

3.1 Dolphin echolocation algorithm

Before starting optimization, search space should be sorted using the following rule:

Search space ordering: For each variable to be optimized during the process, sort alternatives of the search space in an ascending or descending order. If alternatives include more than one characteristic, perform ordering according to the most important one. Using this method, for variable *j*, vector A_j of length LA_j is created which contains all possible alternatives for the j^{th} variable putting these vectors next to each other, as the columns of a matrix, the *Matrix Alternatives*$_{MA*NV}$ is created, in which *MA* is $\max(LA_j)_{\ j=1:NV}$; with *NV* being the number of variables.

Moreover, a curve according to which the convergence factor should change during the optimization process should be assigned. Here, the change of *CF* is considered to be according to the following curve:

$$PP(Loop_i) = PP_1 + (1 - PP_1)\frac{Loop_i^{\ Power} - 1}{(Loops\ Number)^{Power} - 1} \tag{1}$$

PP: Predefined probability.

PP_1 : Convergence factor of the first loop in which the answers are selected randomly.

$Loop_i$: Number of the current loop.

$Power$: Degree of the curve. As it can be seen, the curve in Eq. (1) is a polynominal of *Power* degree.

$Loops \quad Number$: Number of loops in which the algorithm should reach to the convergence point. This number should be chosen by the user according to the computational effort that can be afforded for the algorithm.

Fig. 2 shows the variation of *PP* by the changes of the *Power*, using the proposed formula, Eq. (1).

The flowchart of the algorithm is shown in Fig. 3. The main steps of Dolphin Echolocation (DE) for discrete optimization are as follows:

Initiate *NL* locations for a dolphin randomly.

This step contains creating L_{NL*NV} matrix, in which *NL* is the number of locations and *NV* is the number of variables (or dimension of each location).

Calculate the *PP* of the loop using Eq. (1).

Calculate the fitness of each location.

Fitness should be defined in a manner that the better answers get higher values. In other words the optimization goal should be to maximize the fitness.

Calculate the accumulative fitness according to dolphin rules as follows:

a)

for i = 1 to the number of locations

for j = 1 to the number of variables

find the position of $L(i,j)$ in j^{th} column of the Alternatives matrix and name it as A.

for $k = -R_e$ to R_e

$$AF_{(A+k)j} = \frac{1}{R_e} * \left(R_e - |k|\right) Fitness(i) + AF_{(A+k)j} \tag{2}$$

end

end

end

Where

$AF_{(A+k)j}$ is the accumulative fitness of the $(A+k)^{th}$ alternative (numbering of the alternatives is identical to the ordering of the Alternative matrix) to be chosen for the j^{th} variable; R_e is the effective radius in which accumulative fitness of the alternative A's neighbors are affected from its fitness. This radius is recommended to be not more than 1/4 of the search space; $Fitness$ (i) is the fitness of location *i*.

It should be added that for alternatives close to edges (where $A+k$ is not a valid; $A+k < 0$ or $A+\text{k} > \text{L}A_j$), the *AF* is calculated using a reflective characteristic. In this case, if the distance of an alternative to the edge is less than R_e, it is assumed that the same alternative exists where picture of the mentioned alternative can be seen, if a mirror is placed on the edge.

b) In order to distribute the possibility much evenly in the search space, a small value of ε is added to all the arrays as $AF = AF + \varepsilon$. Here, ε should be chosen according to the way the fitness is defined. It is better to be less than the minimum value achieved for the fitness.

c) Find the best location of this loop and name it "The best location". Find the alternatives allocated to the variables of the best location, and let their *AF* be equal to zero.

In other words:

for j=1: Number of variables

for i=1: Number of alternatives

if i = The best location(j)

$$AF_{ij} = 0 \tag{3}$$

end

end

end

for variable $j_{(j=1 \text{ to } NV)}$, calculate the probability of choosing alternative $i_{(i=1 \text{ to } ALj)}$, according to the following relationship:

$$P_{ij} = \frac{AF_{ij}}{\sum_{i=1}^{LAj} AF_{ij}} \tag{4}$$

6. Assign a probability equal to *PP* to all alternatives chosen for all variables of the best location and devote rest of the probability to the other alternatives according to the following formula:

for j=1: Number of variables

for i=1: Number of alternatives

if i= The best location(j)

$$P_{ij} = PP \tag{5}$$

else

$$P_{ij} = (1 - PP)P_{ij} \tag{6}$$

end

end

end

Calculate the next step locations according to the probabilities assigned to each alternative.

Repeat Steps 2 to 6 as many times as the *Loops Number*.

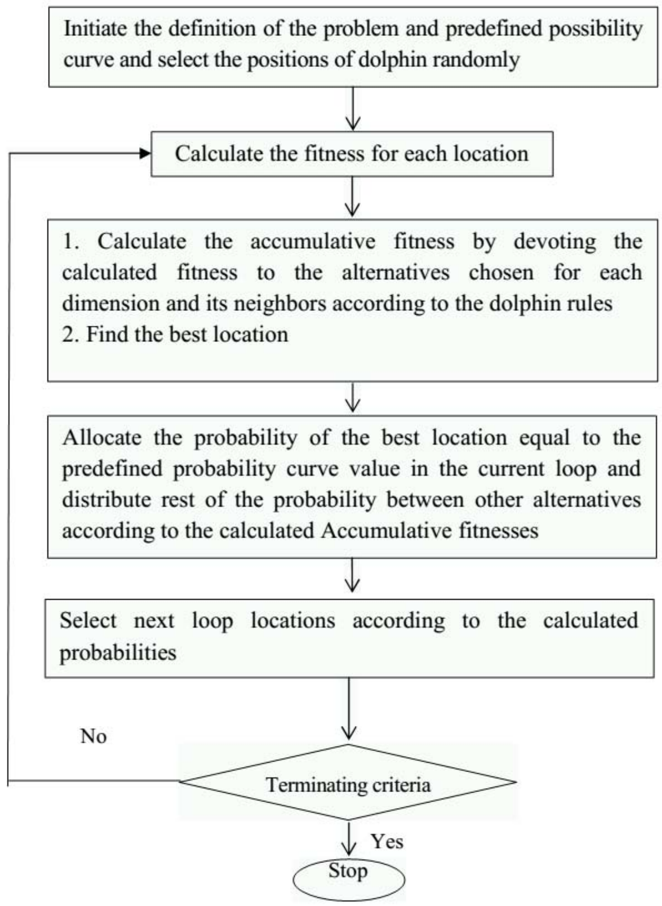


Figure 3. The flowchart of the DE algorithm

4. PROBLEM STATEMENTS

In this paper, the aim is to minimize the weight of the structure under frequency constraints. The optimization problem can be stated mathematically as follows:

$$
\begin{array}{c}
\text{Find } X=(x_1,x_2,x_3,..,x_n) \\
\text{to minimizes Mer } (X) = f(X) \times \text{fpenalty}(X) \\
\text{Subjected to} \\
\omega_j \leq \omega_j^* \qquad \text{for some natural frequencies } j \\
\omega_k \geq \omega_k^* \qquad \text{for some natural frequencies } k \\
x_{imin} \leq x_i \leq x_{imax}
\end{array}
\tag{7}
$$

Where X is the vector containing the design variables, including both nodal coordinates and cross-sectional areas. Here n is the number of variables which is usually chosen with respect to the symmetry and practice requirements. Mer(X) is the merit function; f(X) is the cost function, which is taken as the weight of the structure; $f_{penalty}(X)$ is the penalty function which results from the violations of the constraints corresponding to the response of the structure [8]; ω_j is the i^{th} natural frequency of the structure and ω_j^* is its upper bound. ω_k is the k^{th} natural frequency of the structure and ω_k^* is its lower bound. x_{imin} and x_{imax} are the lower and upper bounds of the design variable x_i, respectively.

The cost function is expressed as

$$f(x) = \sum_{i=1}^{mn} \rho_i L_i A_i \tag{8}$$

where ρ_i is the material density of member i; L_i is the length of member i; and A_i is the cross-sectional area of member i.

The penalty function differs according to the problem.

5. NUMERICAL EXAMPLES

10-bar truss

The 10-bar planar truss shown in Fig. 4 is a common benchmark problem in the field of weight optimization of the structures with frequency constraints. This is a size optimization problem firstly investigated by Grandhi and Venkayya [7] using the optimality algorithm.

A non-structural mass of 454.0 kg is attached to the free nodes. For DE algorithm, all cross sectional areas of members are selected from discrete set of {0.645 0.7 0.8 0.9…50} cm^2. Table1 shows the material properties, variable bounds, and frequency constraints for this example.

This problem is solved for two different values for the elastic modulus as 6.89×10^{10} and 6.98×10^{10} N/m^2 (10^7 psi).

The design vectors and the mass of the corresponding structures obtained by different researchers, is presented in table 2. Frequencies of the optimum answers are presented in Table3. Fig. 5 shows the convergences curve of the best result obtained by DE and compares it with other algorithms.

It can be seen although treat the problem with a discrete optimization method, it achieved nearby results in comparison with other meta-heuristic methods which were a continuous search method.

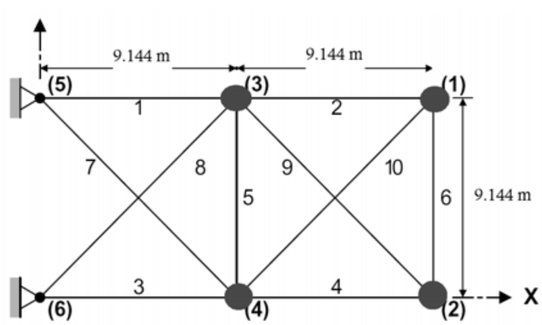


Figure 4. A 10-bar planar truss

Table 1: Material properties, variable bounds and frequency constraints for 10-bar truss structure

Property/unit	Value
E (modulus of elasticity)/N/m^2	6.98×10^{10}
P (Material density)/kg/m^3	2770.0
Added mass/kg	454.0
Design variable lower bound/m^2	0.645×10^{-4}
L (Main bar's dimension)/m	9.144
Constraints on first three frequencies/Hz	$\omega_1 \geq 7$, $\omega_2 \geq 15$, $\omega_3 \geq 20$

Table 2: Optimum answers for 10 bar truss

Element number	Optimal cross-sectional areas (cm^2)						
	Grandhi and Venkayya [17]	Sedaghati [6]	Wang et al. [18]	Lingyun et al. [9]	Gomes [8]	Kaveh and Zolghadr [12]	Kaveh and Zolghadr [13]
					PSO	CSS-BBBC	Democrat PSO
	E=68.9 GPa	E=68.9 GPa	E=68.9 GPa	E=69.8 GPa	E=69.8 GPa	E=69.8 GPa	E=68.9 GPa
1	36.584	38.245	32.456	42.234	37.712	35.274	35.944
2	24.658	9.916	16.577	18.555	9.959	15.463	15.530
3	36.584	38.619	32.456	38.851	40.265	32.11	35.285
4	24.658	18.232	16.577	11.222	16.788	14.065	15.385
5	4.167	4.419	2.115	4.783	11.576	0.645	0.648
6	2.070	4.194	4.467	4.451	3.955	4.880	4.583
7	27.032	20.097	22.810	21.049	25.308	24.046	23.610
8	27.032	24.097	22.810	20.949	21.613	24.340	23.599
9	10.346	13.890	17.490	10.257	11.576	13.343	13.357
10	10.346	11.4516	17.490	14.342	11.186	13.543	12.357
Weight (kg)	594	537.01	553.8	542.75	537.98	529.09	532.39

Table 2: Optimum answers for 10 bar truss (continue)

Element number	Optimal cross-sectional areas (cm^2)			
	Kaveh and Javadi [14]		Present work	
	HRPSO		DE	
	E=68.9 GPa	E=69.8 GPa	E=68.9 GPa	E=69.8 GPa
1	35.54022	34.79250	35.3	34.6
2	15.29310	15.24510	15.1	15.1
3	35.78427	35.56230	36.5	35.5
4	14.60570	13.83640	15.4	15.2
5	0.64554	0.64640	0.645	0.645
6	4.62572	4.58270	4.6	4.6
7	24.77893	25.5346	23.7	23
8	23.31005	22.3002	24	23.7
9	12.48229	11.6142	11.5	12.5
10	12.67468	13.0716	13.5	12.7
Weight (kg)	532.11	524.88	532.814	525.136

Table 3: Frequencies of optimum results

Frequency number	Grandhi and Venkayya [19]	Sedaghati [6]	Wang et al. [20]	Lingyun et al. [9]	Gomes [8]	Kaveh and Zolghadr [12]	Kaveh and Zolghadr [13]
					PSO	CSS-BBBC	Democrat PSO
	E=68.9 GPa	E=68.9 GPa	E=68.9 GPa	E=69.8 GPa	E=69.8 GPa	E=69.8 GPa	E=68.9 GPa
1	7.059	6.992	7.011	7.008	7.000	7.0028	7.000
2	15.895	17.599	17.302	18.148	17.786	16.7429	16.187
3	20.425	19.973	20.001	20.000	20.000	20.0548	20.000
4	21.528	19.977	20.100	20.508	20.063	20.3351	20.021
5	28.976	28.173	30.869	27.797	27.776	28.5232	28.243
6	30.189	31.029	32.666	31.281	30.939	29.2911	29.243
7	54.286	47.628	48.282	48.304	47.297	49.0342	48.769
8	56.546	52.292	52.306	53.306	52.286	51.7451	51.389

Table 3: Frequencies of optimum results(continue)

Frequency number	Kaveh and Javadi [14] HRPSO		Present work DE	
	E=68.9 GPa	E=69.8 GPa	E=68.9 GPa	E=69.8 GPa
1	6.9999	7.0000	7.0003	7.0006
2	16.1752	16.1686	16.2084	16.2035
3	19.9999	20.0015	20.0056	20.0055
4	20.0060	20.0050	20.0231	20.1094
5	28.5156	28.1466	28.1111	28.5985
6	28.9837	29.2724	29.3084	29.1892
7	48.5734	48.5235	48.7437	48.7367
8	51.0823	50.9950	51.3341	51.3418

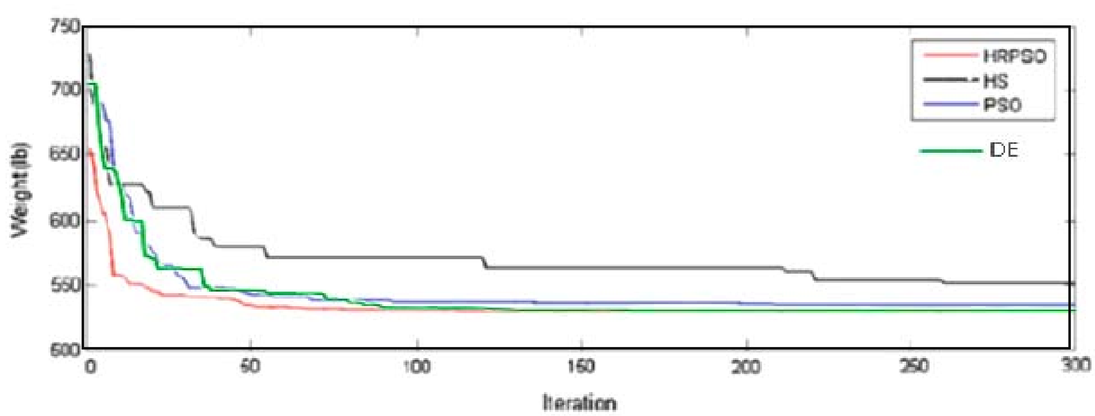


Figure 5. Convergence history for design of 10-bar truss

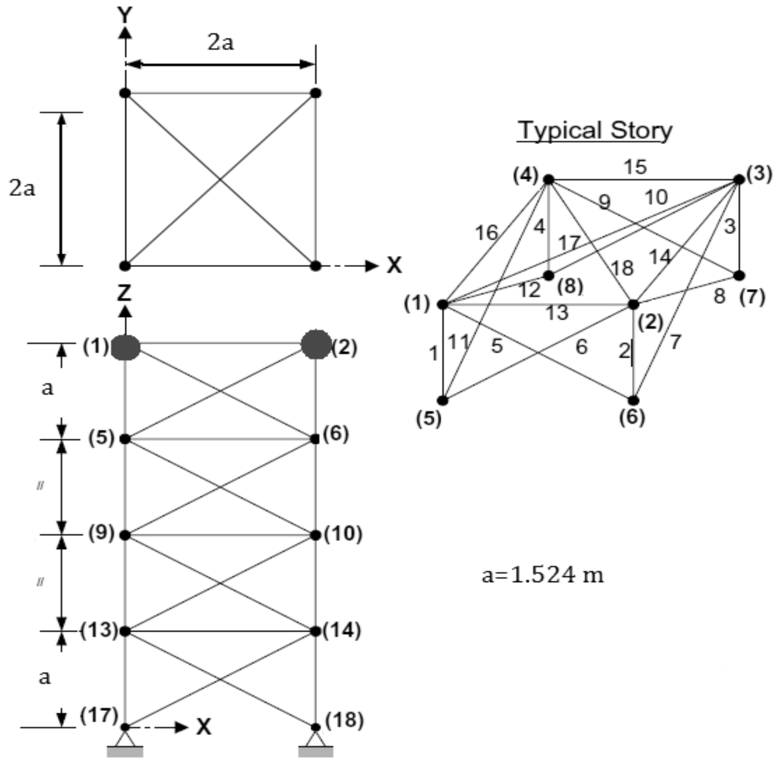


Figure 6. A 72-bar space truss

72-bar space truss

A 72-bar space truss depicted in Fig. 6 is considered. This problem was investigated by Konzelman [21] for the first time. This is a mere size optimization. Four non-structural masses of 2270 kg are attached to the nodes 1–4. Material properties, variable bounds, frequency constrains and added masses are listed in Table 4. The72 elements of the truss are set to 16 design categories according to Table 5. This problem is solved by different elastic modulus as 6.89×10^{10} and 6.98×10^{10} N/m^2 (10^7 psi) for better comparison. Optimum cross-sectional areas obtained with different methods are shown in Table 5. Frequencies of the optimum answers are presented in Table 6.

It can be seen although DE treats the problem with a discrete optimization method, it achieves nearby results in comparison with other meta-heuristic methods which were a continuous search method.

Table 4: Material properties, variable bounds and frequency constraints for 72-bar space truss

Property/unit	Value
E (modulus of elasticity) / N/m^2	$6.98 * 10^{10}$
ρ (Material density) / kg/m^3	2770.0
Added mass / kg	2270
Design variable lower bound / m^2	$0.645*10^{-4}$
Constraints on first three frequencies / Hz	$\omega_1 \geq 4.0$, $\omega_3 \geq 6.0$

Table 5: Optimum answers for 72-bar truss

Element Group		Optimal cross-sectional areas (cm^2)							
		Konzelman [21]	Sedaghati [6]	Gomes [8]	Kaveh and Zolghadr [12]	Kaveh and Javadi [14]		Present work	
					CSS-BBBC	HRPSO		DE	
		E=68.9 GPa	E=68.9 GPa	E=68.9 GPa	E=69.8 GPa	E=68.9 GPa	E=69.8 GPa	E=68.9 GPa	E=69.8 GPa
1	A_1~A_4	3.499	3.499	2.987	2.854	3.9494	3.63529	3.6	4.5
2	A_5~A_{12}	7.932	7.932	7.749	8.301	7.9680	7.83480	8.1	7.6
3	A_{13}~A_{16}	0.645	0.645	0.645	0.645	0.6452	0.64507	0.645	0.645
4	A_{17}~A_{18}	0.645	0.645	0.645	0.645	0.6479	0.64558	0.645	0.645
5	A_{19}~A_{22}	8.056	8.056	8.765	8.202	7.5252	8.41172	8.85	7.6
6	A_{23}~A_{30}	8.011	8.011	8.153	7.043	7.8638	7.96728	8.5	7.8
7	A_{31}~A_{34}	0.645	0.645	0.645	0.645	0.6451	0.64503	0.7	0.645
8	A_{35}~A_{36}	0.645	0.645	0.645	0.645	0.6520	0.64510	0.645	0.645
9	A_{37}~A_{40}	12.812	12.812	13.450	16.328	12.9665	13.29653	11.85	12.3
10	A_{41}~A_{48}	8.061	8.061	8.073	8.299	8.3473	7.87893	8.1	7.9
11	A_{49}~A_{52}	0.645	0.645	0.645	0.645	0.645	0.645	0.645	0.645
12	A_{53}~A_{54}	0.645	0.645	0.645	0.645	0.6451	0.645	0.645	0.645
13	A_{55}~A_{58}	17.279	17.279	16.684	15.048	17.3896	15.9834	17.6	17
14	A_{59}~A_{66}	8.088	8.088	8.159	8.268	8.0068	8.07824	7.55	8.6
15	A_{67}~A_{70}	0.645	0.645	0.645	0.645	0.645	0.64501	0.645	0.645
16	A_{71}~A_{72}	0.645	0.645	0.645	0.645	0.6451	0.64609	0.645	0.645
Weight (lb)		327.605	327.605	328.823	327.507	328.589	324.497	329.422	325.678

Table 6: Frequencies of optimum answers of 72-bar truss

Frequency number	Konzelman [21]	Sedaghati [6]	Gomes [8]	Kaveh and Zolghadr [12]	Kaveh and Javadi [14]		Present work	
				CSS-BBBC	HRPSO		DE	
	E=68.9 GPa	E=68.9 GPa	E=68.9 GPa	E=69.8 GPa	E=68.9 GPa	E=69.8 GPa	E=68.9 GPa	E=69.8 GPa
1	4.000	4.000	4.000	4.000	4.0000	4.0000	4.000	4.000
2	4.000	4.000	4.000	4.000	4.0000	4.0000	4.000	4.000
3	6.000	6.000	6.000	6.004	6.0002	6.0003	6.001	6.008
4	6.247	6.247	6.219	6.2491	6.2639	6.2958	6.261	6.302
5	9.074	9.074	8.976	8.9726	9.1166	9.1215	9.15	9.168

A 52-bar dome-like truss

The initial topology of a 52-bar dome truss is depicted in Fig.7. Material properties, frequency constraints and variable bounds for this example are summarized in Table 7. Non-structural masses of 50 kg are attached to all free nodes. All of the elements of the structure are classified in eight groups according to Table 8.All free nodes are allowed to move in a manner that the symmetry of the truss remains. Their movement can vary by ±2 m. Thus this is a shape and size optimization problem, with both the cross-sectional area of the members and the nodal coordinates considered as variables. This example has been investigated recently by Kaveh et al [11-14] with different hybrid meta-heuristic algorithms.

Table 7: Material properties, variable bounds and frequency constraints of 52-bar space truss

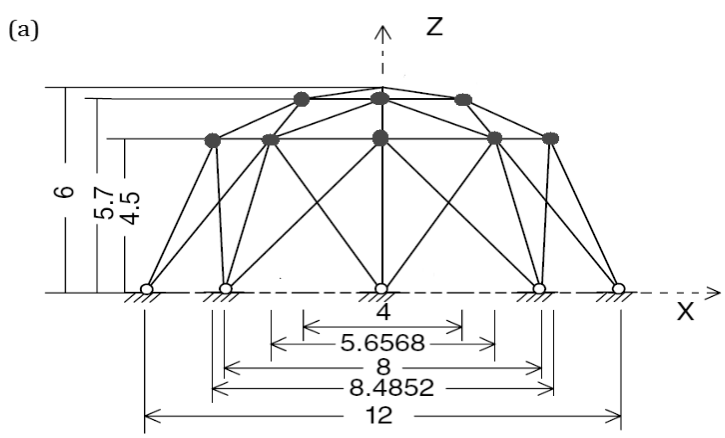
Property/unit	Value
E (modulus of elasticity) / N/m^2	2.1* 10^{11}
ρ (Material density) / kg/m^3	7800
Added mass / kg	50
Allowable range for cross-sections / m^2	$0.0001 \leq A \leq 0.001$
Constraints on first two frequencies / Hz	$\omega_1 \leq 15.916$, $\omega_2 \geq 28.648$

Table 8:Element grouping of 52-bar space truss

Group number	Elements
1	1-4
2	5-8
3	9-16
4	17-20
5	21-28
6	29-36
7	37-44
8	45-52

Table 9 represents results obtained by the various methods and Table 10 shows corresponding natural frequencies. Fig. 8 compares the convergence curve for the best result obtained by DE with other algorithms.

It can be seen that DE leads to results nearby the best solution obtained so far, with a reasonable convergence rate.



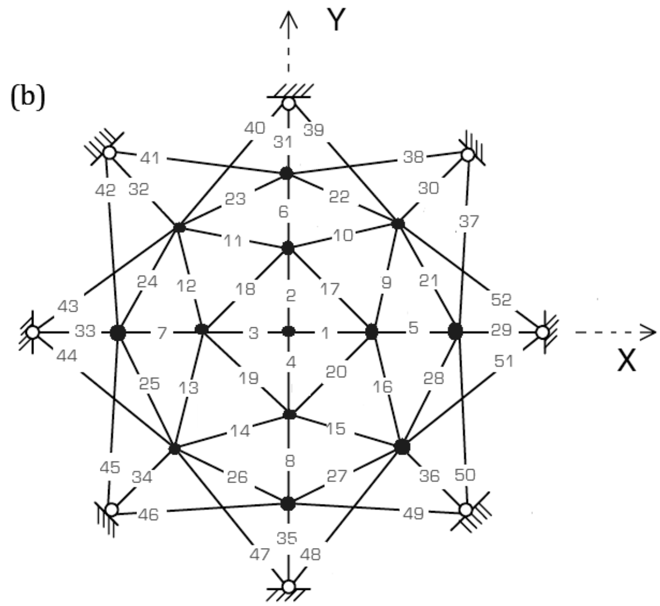


Figure 7. A 52-bar dome-like truss

Table 9: Optimum results of 52-bar truss

Variable	Initial	Lin et al. [7]	Lingyun et al. [9]	Gomes [8]	Kaveh and Zolghadr [12]	Kaveh and Javadi [14]	Kaveh and Zolghadr [13]	Present work
				PSO	CSS-BBBC	HRPSO	Democrat PSO	DE
Z_A (m)	6.000	4.3201	5.8851	5.5344	5.331	5.82857	6.1123	5.72
X_B (m)	2.000	1.3153	1.7623	2.0885	2.134	2.24360	2.2343	2.14
Z_B (m)	5.700	4.1740	4.4091	3.9283	3.719	3.72064	3.8321	3.78
X_F (m)	4.000	2.9169	3.4406	4.0255	3.935	3.95665	4.0316	3.94
Z_F (m)	4.500	3.2676	3.1874	2.4575	2.500	2.50008	2.5036	2.52
A_1 (cm^2)	2.0	1.00	1.0000	0.3696	1.0000	1.00000	1.0001	1.1
A_2 (cm^2)	2.0	1.33	2.1417	4.1912	1.3056	1.13655	1.1397	1.2
A_3 (cm^2)	2.0	1.58	1.4858	1.5123	1.4230	1.22183	1.2263	1.2
A_4 (cm^2)	2.0	1.00	1.4018	1.5620	1.3851	1.48666	1.3335	1.6
A_5 (cm^2)	2.0	1.71	1.911	1.9154	1.4226	1.39548	1.4161	1.4
A_6 (cm^2)	2.0	1.54	1.0109	1.1315	1.0000	1.00000	1.0001	1.0
A_7 (cm^2)	2.0	2.65	1.4693	1.8233	1.5562	1.55152	1.5750	1.5
A_8 (cm^2)	2.0	2.87	2.1411	1.0904	1.4485	1.41820	1.4357	1.5
Weight (kg)	338.69	298.0	236.046	228.381	197.309	193.361	195.351	195.852

Table 10: Frequencies of optimum answers of 52-bar truss

Frequency number	Initial	Lin et al. [7]	Lingyun et al. [9]	Gomes [8]	Kaveh and Zolghadr [12]	Kaveh and Javadi [14]	Kaveh and Zolghadr [13]	Present work
				PSO	CSS-BBBC	HRPSO	Democrat PSO	DE
1	22.69	15.22	12.81	12.751	12.987	11.6853	11.315	11.4102
2	25.17	29.28	28.65	28.649	28.648	28.6486	28.648	28.6499
3	25.17	29.28	28.65	28.649	28.679	28.6486	28.648	28.6499
4	31.52	31.68	29.54	28.803	28.713	28.6509	28.650	28.7566
5	33.80	33.15	30.24	29.230	30.262	29.1298	28.688	29.6327

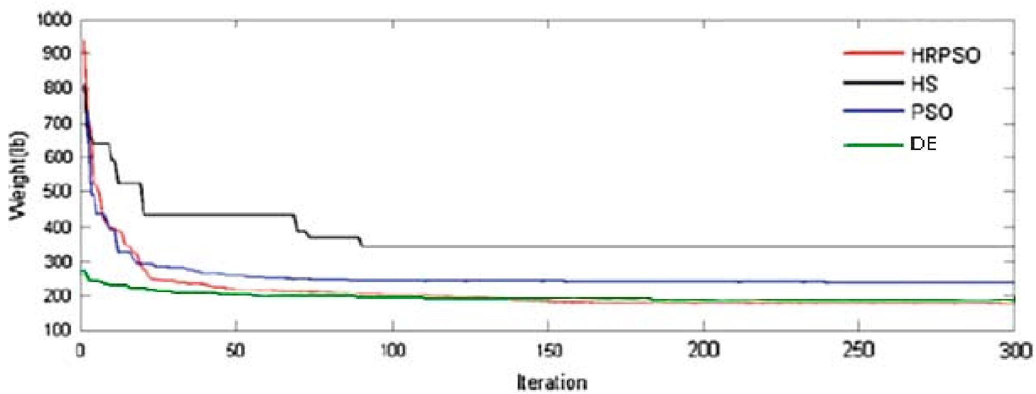


Figure 8. Convergence history for design of 52-bar truss

A simply supported 37-bar bridge

Fig. 9 indicates the initial configuration of the simply supported 37-bar bridge. This example was first investigated by Wang et al. [20]. The nodes exists on lower chord are attached to non-structural mass of 10 kg. The elements of this chord are considered as bar elements with fixed rectangular cross section area of 4×10^{-3} m^2. The other bars are considered as simple bar elements with initial sectional areas of 1×10^{-3} m^2. In this example, the elastic modulus is 210 GPa and the material density is ρ = 7,800 kg/m^3 for all elements. All nodes of the upper chord are permitted to shift in y direction in a symmetrical manner and all the diagonal upper chord bars are allowed to vary its cross-sectional areas with the lower bound of A =1×10^{-3} m^2. The first three natural frequencies are subjected to constraints so that $\omega1 \geq 20$ Hz, $\omega2 \geq 40$ Hz, $\omega3 \geq 60$ Hz. Therefore this is a size and shape optimization problem with frequency constraints

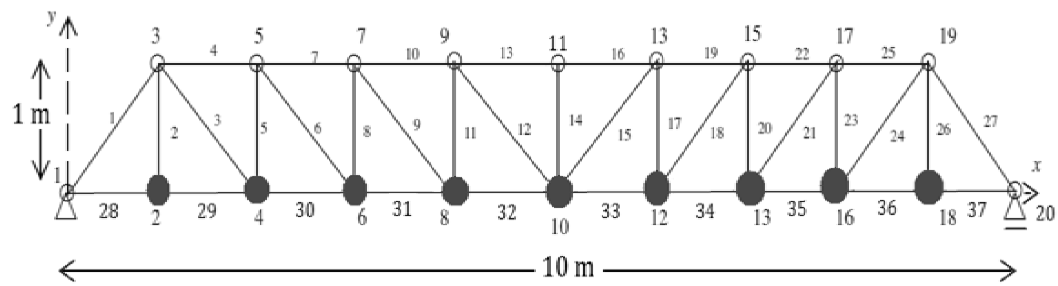


Figure 9. A 37-bar truss

Table 11: Optimum answers for 37-bar truss

Variable group	Initial design	Wang et al. [20]	Lingyun et al. [9]	Gomes [8]	Kaveh and Javadi [14]	Kaveh and Zolghadr		Present work
				PSO	HRPSO	Standard CSS [11]	Democrat PSO [13]	DE
Y_3 , Y_{19} (m)	1.0	1.2086	1.1998	0.9637	1.07444	0.8726	0.9482	1.04
Y_5 , Y_{17} (m)	1.0	1.5788	1.6553	1.3978	1.49568	1.2129	1.3439	1.40
Y_7 , Y_{15} (m)	1.0	1.6719	1.9652	1.5929	1.73243	1.3826	1.5043	1.64
Y_9, Y_{13} (m)	1.0	1.7703	2.0737	1.8812	1.89449	1.4706	1.6350	1.74
Y_{11} (m)	1.0	1.8502	2.3050	2.0856	1.96970	1.5683	1.7182	1.84
A_1, A_{27} (cm^2)	1.0	3.2508	2.8932	2.6797	2.85176	2.9082	2.6208	2.7
A_2, A_{26} (cm^2)	1.0	1.2364	1.1201	1.1568	1.00000	1.0212	1.0397	1.0
A_3, A_{24} (cm^2)	1.0	1.0000	1.0000	2.3476	1.83410	1.0363	1.0464	1.0
A_4, A_{25} (cm^2)	1.0	2.5386	1.8655	1.7182	1.88766	3.9147	2.7163	2.4
A_5, A_{23} (cm^2)	1.0	1.3714	1.5962	1.2751	1.06267	1.0025	1.0252	1.2
A_6, A_{21} (cm^2)	1.0	1.3681	1.2642	1.4819	1.80266	1.2167	1.5081	1.2
A_7, A_{22} (cm^2)	1.0	2.4290	1.8254	4.6850	1.93387	2.7146	2.3750	2.2
A_8, A_{20} (cm^2)	1.0	1.6522	2.0009	1.1246	1.24946	1.2663	1.4498	1.3
A_9, A_{18} (cm^2)	1.0	1.8257	1.9526	2.1214	1.87404	1.8006	1.4499	1.9
A_{10}, A_{19} (cm^2)	1.0	2.3022	1.9705	3.8600	1.95716	4.0274	2.5327	2.2
A_{11}, A_{17} (cm^2)	1.0	1.3103	1.8294	2.9817	1.24410	1.3364	1.2358	1.3
A_{12}, A_{15} (cm^2)	1.0	1.4067	1.2358	1.2021	1.77792	1.0548	1.3528	1.4
A_{13}, A_{16} (cm^2)	1.0	2.1896	1.4049	1.2563	1.80643	2.8116	2.9144	2.5
A_{14} (cm^2)	1.0	1.0000	1.0000	3.3276	1.00000	1.1702	1.0085	1.0
Weight (kg)	336.30	366.50	368.84	377.20	364.72	362.84	360.40	361.03

Table 11 observes the comparison of the results of utilized algorithm with the outcomes of other algorithms. And Table 12 shows the corresponding natural frequencies. It can be seen that DE obtains near optimum answer although it is dealt with a continuous problem as a discrete algorithm.

Table 12: Frequencies of optimum answers of 37-bar truss (continue)

Frequency number	Initial design	Wang et al. [20]	Lingyun et al. [9]	Gomes [8]	Kaveh and Javadi [14]	Kaveh and Zolghadr		Present work
				PSO	HRPSO	Standard CSS [11]	Democrat PSO [13]	DE
1	8.8778	20.0850	20.0013	20.0001	20.0000	20.0000	20.0194	20.0334
2	29.2135	42.0743	40.0305	40.0003	40.0160	40.0693	40.0113	40.3460
3	48.5539	62.9383	60.0000	60.0001	60.0101	60.6982	60.0082	60.0644
4	67.7487	74.4539	73.0444	73.0440	79.3488	75.7339	76.9896	76.4469
5	84.2484	90.0576	89.8244	89.8240	100.2331	97.6137	97.2222	96.4887

6. CONCLUSION

In this study, DEO is applied for optimum design of truss structures with frequency constraints. The new method has the advantage of working according to the computational effort that user can afford for his/her optimization. In this algorithm, the convergence factor defined in [17] is controlled in order to perform a suitable optimization.

For the examples optimized in this paper, the DE achieves better or nearby results compared to other existing meta-heuristic algorithms. The authors believe that the results achieved from meta-heuristics are mostly dependent on the parameter tuning of the algorithms. It is also believed that by performing a limited number of numerical examples, one cannot correctly conclude the superiority of one method with respect to the others. Dolphin echolocation is an optimization algorithm that has the capability of adopting itself by the type of the problem in hand, having a reasonable convergence rate, and leading to an acceptable optimum answer in a number of loops specified by the user.

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