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MODERN SWARM-BASED ALGORITHMS FOR THE TENSION/COMPRESSION SPRING DESIGN OPTIMIZATION PROBLEM

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Abstract: The scientific literature is enriched with large number of optimization problems of various levels of difficulty. Constrained optimization tasks in the field of engineering design have grown very popular in the last years and many authors have implemented different algorithms in order to obtain optimal solutions. One of the well-known engineering optimization problems is so-called tension/compression spring design. Several novel and very popular swarm-based intelligent algorithms are implemented in this study in order to minimize weight of the string and to obtain comparative results. Graphical representations of convergence curves as well as statistical results have been also included in this brief study. Swarm-based algorithms performed well and fast for the tension/compression design problem.
Keywords: swarm-based algorithms, spring design, optimization, metaheuristics

1. INTRODUCTION

Optimization may consider a number of different problems whose complexity mostly depends on the forms of objective functions and its constraints [1]. Optimization problems can be found in many areas of engineering and industry and can be classified in different ways which requires different optimization techniques to solve them. Engineering design problems are one of the well-studied constrained optimization problems that typically consider minimization or maximization of objective functions by finding appropriate values of design variables (design parameters) according to the set of specific constraints [2]. Real-world design problems may include a large number of these variables and also a number of different linear or non-linear constraints which increase complexity when making function evaluations. In that sense, efficient and flexible optimization techniques are required.

To deal with constrained optimization problems in engineering design a number of different metaheuristic algorithms have been proposed. According to [3], metaheuristic algorithms can be grouped in three main categories, evolutionary, physics-based, swarm-based and human-based group, such as represented in Fig.1. The first group of techniques is inspired by natural evolution principles. The second one imitates physical processes that can be found in our universe. The third group of algorithms is inspired by social behavior of animals and creatures in the nature. The last group covers human-based solutions that imitate human behavior in various activities.

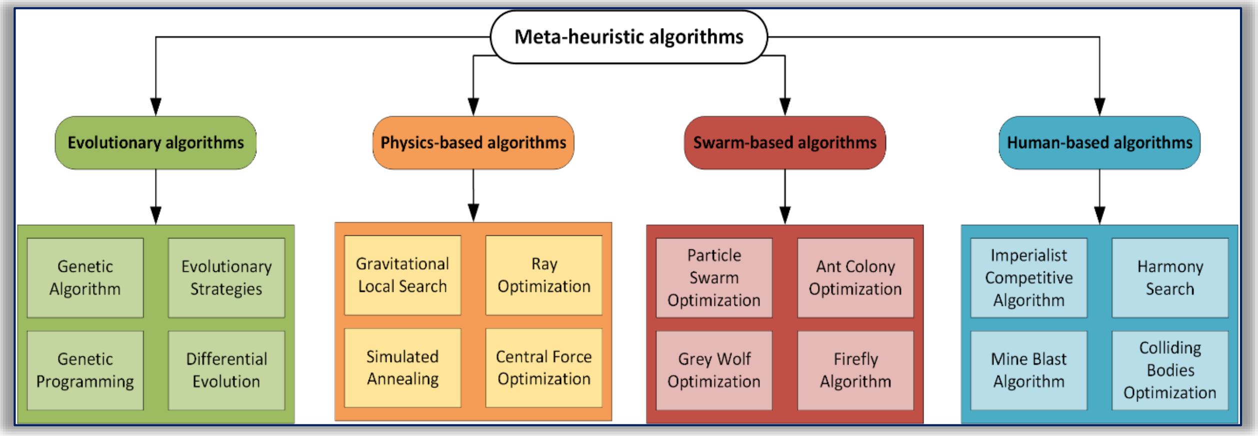

Figure 1. A classification of metaheuristic algorithms

The emphasis in this paper will be placed on the third group of metaheuristic algorithms which are studied and introduced within the scientific field called Swarm intelligence. Swarm-based metaheuristics are population-based algorithms where a randomly generated population of individuals (potential candidates) cooperate among each other and statistically over generations become better and better and ultimately they are able to find good enough (satisfactory) solutions for a problem at hand [4]. Using a set of specific rules, swarm-based algorithms define the position vector and change it over iterations. This is achieved in two main phases, exploration, in which algorithm performs abrupt changes to ensure different regions of search space are checked, and exploitation where algorithm directs search around the best possible solutions found so far [5]. Exploitation improves local search capabilities, while exploration leans towards global search. The main advantages of these stochastic techniques are problem independence, simplicity of understanding and implementation, and adaptability to difficulties of real-world problems.

In that sense, several swarm-based metaheuristics will be employed to solve the optimization problem from engineering design called tension/compression string design problem. Comparative results will be obtained in order to show performances of the proposed algorithms and ultimately, proposals for algorithm adjustments, improvements or modifications will be highlighted.

2. THE TENSION/COMPRESSION STRING DESIGN PROBLEM

The tension/compression string design problem was firstly introduced in [6,7]. Objective function for this optimization task is to minimize the weight of the tension/compression string which is shown in Figure 2 and Figure 3.

Figure 2. Tension/compression spring schematic 2D representation [9,10]

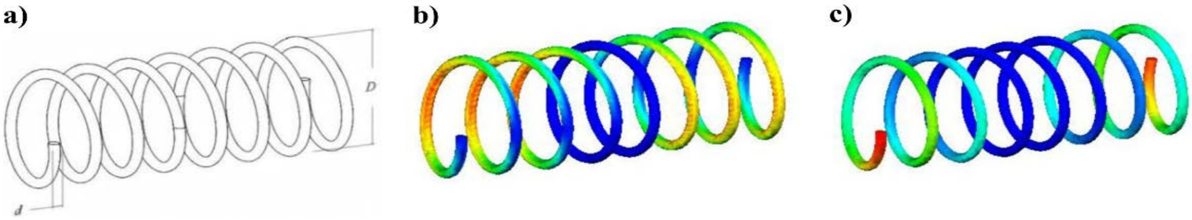

Figure 3. Tension/compression spring graphical representation:
(a) 3D schematic, (b) stress heatmap (c) displacement heatmap [3]

The optimal design of the spring must satisfy constraints on minimum deflection, shear stress, surge frequency and limits on outside diameter and decision variables [8]. Three continuous decision variables are taken into account: wire diameter (d or x_1), mean coil diameter (D or x_2) and number of active coils (P or x_3). Mathematical formulation of the tension/compression spring design problem is given as follows [3,9,10]:

Decision variables:

$$\vec{x} = [x_1, x_2, x_3] = [d, D, P] \tag{1}$$

Minimize:

$$f(\vec{x}) = (x_3 + 2)x_2 x_1^2 \tag{2}$$

Subject to inequality constraints:

$$g_1(\vec{x}) = 1 - \frac{x_2^3 x_3}{71785 x_1^4} \leq 0 \tag{3}$$

$$g_2(\vec{x}) = \frac{4x_2^2 - x_1 x_2}{12566(x_2 x_1^3 - x_1^4)} + \frac{1}{5108 x_1^2} \leq 0 \tag{4}$$

$$g_3(\vec{x}) = 1 - \frac{140{,}45 x_1}{x_2^2 x_3} \leq 0 \tag{5}$$

$$g_4(\vec{x}) = \frac{x_1 + x_2}{1{,}5} - 1 \leq 0 \tag{6}$$

Bound range:

$$0{,}05 \leq x_1 \leq 2{,}00 \tag{7}$$

$$0{,}25 \leq x_2 \leq 1{,}30 \tag{8}$$

$$2{,}00 \leq x_3 \leq 15{,}0 \tag{9}$$

3. RESULTS AND DISCUSSION

In order to obtain satisfactory results, the tension/compression string design problem has been tested using several modern swarm-based metaheuristic algorithms. Comparative results have been obtained and traditional non-modified metaheuristics have shown their performances. Among a large number of algorithms introduced in scientific community, we have adopted the following ones in this study: Crow Search Algorithm (CSA) [10], Grey Wolf Optimizer (GWO) [11], Particle Swarm Optimization (PSO) [12], Whale Optimization Algorithm (WOA) [3], Ant Lion Optimizer (ALO) [13], Bat Algorithm (BA) [14], Firefly Algorithm (FA) [15], Artificial Bee Colony (ABS) [16], Seagull Optimization Algorithm (SOA) [17] and Cuckoo Search [18]. Most of these metaheuristics are introduced in the last decade and therefore can be considered as fairly modern optimization techniques. Comparison of the statistical results obtained by the aforementioned algorithms for the tension/compression string design problem are given in Table 1. All of the metaheuristics have been run 50 times with the standard set of parameters for each. Number of iterations (1000) and number of search agents/individuals (50) are the only two parameters that were adopted for all metaheuristics.

Table 1. Comparison of statistical results obtained by novel swarm-based metaheuristics

Algorithm	Worst value	Best value	Average value	Standard deviation
CSA	0.016523	0.012876	0.014114	0.0007643
GWO	0.012765	0.01267	0.012711	2.1078e-05
PSO	0.015369	0.012667	0.01328	0.00078137
WOA	0.01688	0.01267	0.013674	0.00097938
ALO	0.017549	0.012666	0.01339	0.0010299
BA	0.016062	0.012669	0.012963	0.00061963
FA	0.013594	0,012667	0.012768	0.00016988
ABC	0.018023	0.012918	0.013383	0.00080648
SOA	0.01314	0.0127	0.012767	5.9998e-05
CS	0.013741	0.012668	0.012849	0,00021589

Table 2 and Table 3 show the best solutions, i.e. best values for wire diameter, mean coil diameter and number of coils as well as values of the constraints obtained by GWO and WOA metaheuristics respectively.

Table 2. The best solution obtained by GWO algorithm for the tension/compression string design

Parameter	x_1 (d)	x_2 (D)	x_3 (P)	g_1
Value	0.051791	0.359144	11.1545	-0.00047155
Parameter	g_2	g_3	g_4	$f(\vec{x})$
Value	-7.1177e-05	-4.0558	-0.72604	0.012672

Table 3. The best solution obtained by WOA algorithm for the tension/compression string design

Parameter	x_1 (d)	x_2 (D)	x_3 (P)	g_1
Value	0.051791	0.359144	11.1545	-0.00047155
Parameter	g_2	g_3	g_4	$f(\vec{x})$
Value	-7.1177e-05	-4.0558	-0.72604	0.012672

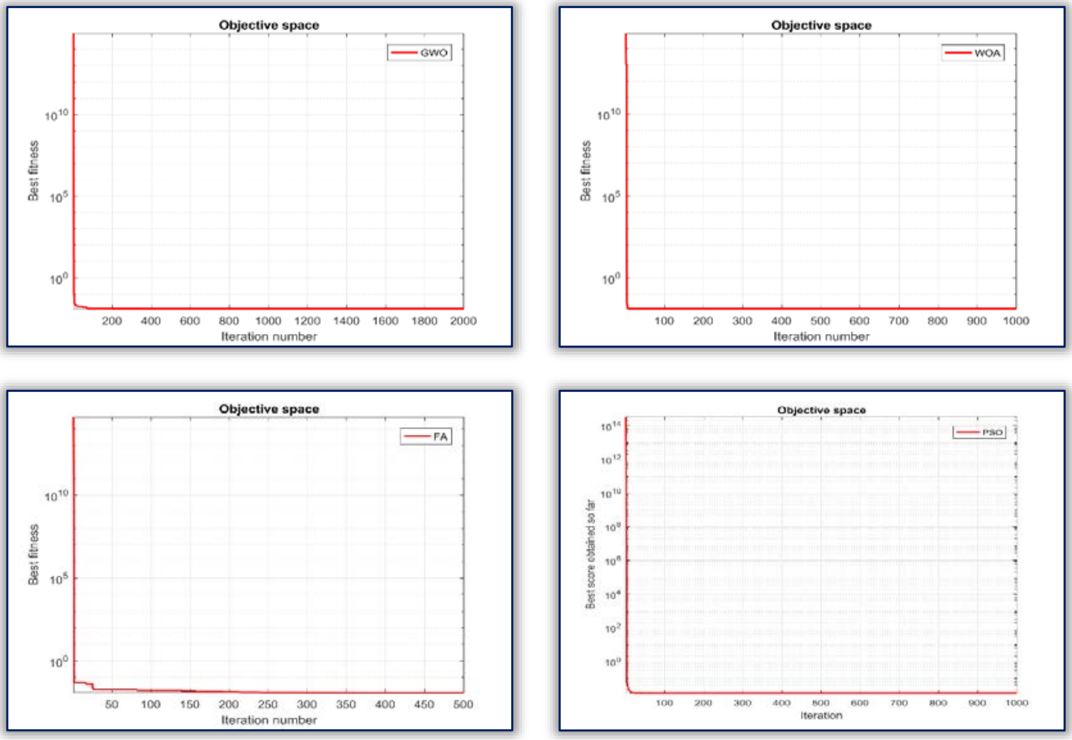

Figure 4. Convergence rates of GWO, WOA, FA and PSO algorithms respectively for finding the best possible fitness of tension/compression string design problem

Figure 4 represents the convergence curves for four swarm-based metaheuristics selected from the study. As it can be noticed, all the algorithms clearly express fast convergence towards the best fitness for this simple optimization task. With additional tuning of parameters and improvements in balance between exploitation and exploration phases, these modern metaheuristics could find more promising results for constrained engineering design problems.

4. CONCLUSION

Brief study represented in this paper considered the implementation of several modern swarm-based metaheuristic algorithms on constrained optimization problem well-known in the literature as the tension/compression string design problem. After short introduction to optimization in engineering design, the emphasis was put on metaheuristic algorithms, primarily on swarm-based group of metaheuristics. Their popularity has grown in years due to their simplicity, flexibility, problem independence and ease of implementation. Afterwards, tension/compression string problem was defined and mathematical formulations were given. Then, several swarm-based algorithms were applied and comparative results were obtained. Main statistical parameters were included in this comparative analysis and two of the best solutions were pointed out. Convergence curves represented the rate of algorithms convergence toward best values. Short discussion was made to point out the significance of algorithm parameter tuning and improvements that should be considered in future studies in order to boost their performances and improve balance between exploration and exploitation phases.

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