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Optimum Design of Trusses by Cuckoo Search

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***Abstract*—**Optimal design of structure has a main role in reduction of material usage which leads to deduction in the final cost of construction projects. Evolutionary approaches are found to be more successful techniques for solving size and shape structural optimization problem since it uses a stochastic random search instead of a gradient search. By reviewing the recent literature works the problem found was the optimization of weight. A new meta-heuristic algorithm called as Cuckoo Search (CS) Algorithm has used for the optimization of the total weight of the truss structures. This paper has used set of 10 bars and 25 bars trusses for the testing purpose. The main objective of this work is to reduce the number of iterations, weight and the total time consumption. In order to demonstrate the effectiveness of the present method, minimum weight design of truss structures is performed and the results of the CS are compared with other algorithms.

***Keywords*—**Cuckoo search algorithm, levy's flight, meta-heuristic, optimal weight.

I. Introduction

INVESTIGATION in the field of structural optimization was started in the early 1960's. Since then, truss structures are most habitually used for evaluating the performance of any particular optimization technique due to the following reasons [1], [2]. Truss design generally starts with a given distance that the structure spans and the loading conditions. The designer determines the overall profile of the truss (geometry), the number of members and their arrangements (topology), and the shape and cross sectional areas of member [3]. The goal of truss optimization is to utilize the material up to the maximum extent in order to result in the lightest structure while satisfying all the design, manufacturing and other physical constraints. Therefore, in sizing optimization of Plane and Space trusses the objective function usually aims at minimizing the weight of the structure under certain behavioral constraints on stresses and displacements [4], [5]. The design variables are most frequently chosen to be cross-sectional areas of the members of the structure. The problem of weight minimization becomes a combinatorial optimization problem necessitating an efficient algorithm to find an optimal solution [6]. Many research works have been successfully carried out on the optimum structural designs by means of several soft computing tools such as Genetic Algorithm (GA) [7]-[12], Simulated Annealing (SA) [13], Ant Colony Optimization and so on.

Most of these optimization techniques encounter some common limitations such as Enormous computational time, premature convergence and Algorithm termination at sub-optimal points. Therefore, the chance of generating a global optimum or a near optimal solution in a reasonable computational time becomes less [14].

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In this paper, one of meta-heuristic method, the so-called Cuckoo Search algorithm [15], is utilized to determine optimum weight of trusses. This algorithm was recently developed by Yang and Deb and is based on the obligate brood parasitic behavior of some cuckoo species together with the Levy's flight behavior of some birds and fruit flies [16]. CS algorithm is one of the latest additions to the group of nature inspired optimization heuristics. It has been introduced by Young and Deb in 2009 and had been proved to be a promising tool for solving hard optimization problems.

Cuckoo birds attract attention because of their unique aggressive reproduction strategy. Cuckoos engage brood parasitism. It is a type of parasitism in which a bird (brood parasite) lays and abandons its eggs in the nest of another species. Some species such as the Ani and Guira cuckoos lay their eggs in communal nests; they may destroy others' eggs to increase the hatching probability of their own eggs. Some host birds do not behave friendly against intruders and engage in direct conflict with them. In such situation host bird will throw those alien eggs away. In other situations, more friendly hosts will simply abandon its nest and build a new nest elsewhere.

In Cuckoo Search algorithm, potential solutions reassemble to Cuckoo eggs. Nature systems are complex and thus, they cannot be modeled by computer algorithms in its basic form. Simplification of natural systems is necessary for successful implementation in computer algorithms. One approach is to adapt Cuckoo Search algorithm through three below presented approximation rules:

- Cuckoos chose random location (nest) for laying their eggs. Artificial cuckoo can lay only one egg at the time.
- Elitist selection process is applied, so only the eggs with highest quality are passed to the next generation
- Host nests number is not adjustable. Host bird discovers cuckoo egg with probability p_d ε [0, 1]. If cuckoo egg is disclosed by the host, it may be thrown away, or the host may abandon its own nest and commit it to the cuckoo intruder.

To make the things even simpler, the last assumption can be approximated by the fraction of p_d of m nests that are replaced by new nests with new random solutions. Considering maximization problem, the quality (fitness) of a solution can simply be proportional to the value of its objective function. Other forms of fitness can be defined in a similar way the fitness function is defined in genetic algorithms and other evolutionary computation algorithms [3]. Here one egg in a nest represents a solution and a cuckoo egg represents a new solution. The aim is to use the new and potentially better solutions (cuckoos) to replace worse solutions that are in the nests. While generating new solutions, x_i^{t+1} for the i[th] Cuckoo, a Lévy flight is performed using the following equation.

$$x_i^{t+1} = x_i^t + Q \oplus Levy(\gamma) \qquad (1)$$

where Q > 0 is the step size parameter and should be chosen considering the scale of the problem and is set to unity in the CS. It should be noted that in this new version, the solutions' current positions are used instead of the best solution obtained so far with the origin of the Levy's flight.

Pseudo Code for Cuckoo Search Algorithm

Start
 Generating initial population of m host nests x_i (i=1, 2…m)
While (S<MaxGenerations) and (! termin.condit.)
 Move a cuckoo randomly via Levy's flights
 Evaluate its fitness F_i
 Randomly choose nest among n available nests (for example j)
If (Fi < Fj)
 Replace j by the new solution;
 Fraction p_d of worse nests are abandoned and new nests are being built;
 Keep the best solutions or nests with quality solutions;
 Rank the solutions and find the current best
End while
 Post process and visualize results
End

A. Levy's Flights as Random Walks

Levy's flights have been observed among foraging patterns of albatrosses, fruit flies and spider monkeys [16]. In nature, animals search for food in a random or quasi-random manner. In general, the foraging path of an animal is effectively a random walk because the next move is based on the current location/state and the transition probability to the next location. The direction it chooses depends implicitly on a probability which can be modeled mathematically. For example, various studies have shown that the flight behavior of many animals and insects has demonstrated the typical characteristics of Levy's flights.

Levy's flight is a random walk in which the step lengths are distributed according to a Levy's distribution function. Continuous Time Random Walks (CTRW) is a random walk in which the step lengths and the waiting time are distributed according to Levy distributions. A recent study by Reynolds and Frye shows that fruit flies or *Drosophila melanogaster*; explore their landscape using a series of straight flight paths punctuated by a sudden turn, leading to a Levy's flight-style intermittent scale-free search pattern. Studies on human behavior of hunter-gatherer foraging patterns also show the typical feature of Levy's flights. Even light can be related to Levy's flights.

Optimum Design of Truss Structures Using Cuckoo Search Algorithm

- Initialize the Cuckoo Search algorithm parameters:

The CS parameters are set in the first step. These parameters are number of nests (n), step size parameter (α) and maximum number of analyses as the stopping criterion.

- Selection of nest:

In our process the nest resembles the number of truss used in a single process. The nests are set to be number of bars.

- Generate initial nests or eggs of host birds:

The initial locations of the nests are determined by the set of possible cross sections values, length and density values which are taken in the random form.

- Evaluation of fitness:

Fitness calculation is done by the weight form and it is given by,

$$C = \sum_{g=1}^{n} \rho A_i L_i \qquad (2)$$

A_i is the cross-sectional area of the i[th] member, L_i is the length of the i[th] member, and ρ is the weight density of the material

- Generate new Cuckoos by Levy's flights:

In this step all of the nests except for the best so far are replaced in order of quality by new Cuckoo eggs produced with Levy's flights from their positions as

$$x_i^{t+1} = x_i^t + Q \oplus Levy(\gamma) \qquad (3)$$

where Q>0 is step size. This parameter should be related to the scales of problem the algorithm is trying to solve. In most cases, Q can be set to the value of 1 or some other constant. The sign represents entry-wise multiplications. If (F_i < F_j) Replace j by the new solution and fraction $_{Pa}$ of worse nests are abandoned and new nests are being built. Now keep the best solutions or bars with quality solutions.

- Termination criterion:

The generation of new Cuckoos and the discovery of the alien eggs are performed alternately until a termination criterion is satisfied. The maximum number of structure analyses is considered as the algorithm's termination criterion. It is clear that this algorithm can be extended to the more complicated case where each nest has multiple eggs representing a set of solutions.

B. Numerical Example of Truss

In our proposed method we have improved the weight of all the bars. The final results are compared to the solutions of other methods to demonstrate the efficiency of the CS. We have tried to vary the number of host nests (or the population size of n). From our simulations, we found that n=10 and 8, which are efficient for design examples. The examples contain 10 bars plane truss with continuous design variables and 25 bars transmission tower with continuous search space. The list of possible length, taken from the American Institute of Steel

Construction Manual is L_i={1.62, 1.80, 1.99, 2.13, 2.38, 2.62, 2.63, 2.88, 2.93, 3.09, 3.13, 3.38, 3.47, 3.55, 3.63, 3.84, 3.87, 3.88, 4.18, 4.22, 4.49, 4.59, 4.80, 4.97, 5.12, 5.74, 7.22, 7.97, 11.5, 13.5, 13.9, 14.2, 15.5, 16.0, 16.9, 18.8, 19.9, 22.0, 22.9, 26.5, 30.0, 33.5}(in). The set of available areas are A_i = {0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.1, 2.2, 2.3, 2.4, 2.5, 2.6, 2.8, 3.0, 3.2, and 3.4} (in²). The density is given by ρ= 0.10 lb/in^3 (2,770 kg/m^3).

The objective function of the problem is to minimize the weight of the structure.

$$C = \sum_{g=1}^{n} \rho A_i L_i \tag{4}$$

where C is the weight and it should be optimized to improve the result of the proposed work.

A 10-Bar Plane Truss

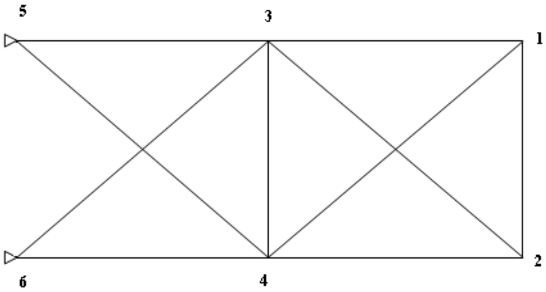

Fig. 1 Structure of 10- bar plane truss

A plane truss is idealized as a system of members lying in a plane and interconnected at hinged joints. All applied forces are assumed to act in the plane of the structure, and all external couples have their moment vectors normal to the plane. The loads may consist of concentrated forces applied to the joints, as well as loads that act on the members themselves. For purposes of analysis, the latter loads may be replaced by statically equivalent loads acting at the joints. Then the analysis of a truss subjected only to joint loads will result in axial forces of tension and compression in the members. The determination of all such stress resultants constitutes the complete analysis of the forces in the members of a truss.

A 25-Bar Space Truss

The 25-bar transmission tower is widely used in structural optimization to verify various meta-heuristic algorithms. The topology of a 25-bar space truss structure is shown in Fig. 2 Twenty-five members are categorized into eight groups, as follows: (1) A1, (2) A2 –A5, (3) A6–A9, (4) A10–A11, (5) A12–A13, (6) A14–A17, (7) A18–A21, and (8) A22–A25.

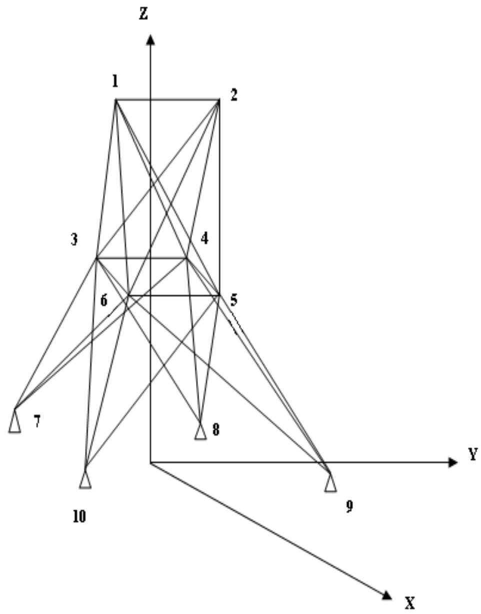

Fig. 2 Structure of 25- bar space truss

II. Results and Discussion

The results produced with the cuckoo are compared with other algorithm methods and have proved that the results obtained by cuckoo provide best output than other methods. In the existing work GA provides best result and to overcome that part in our proposed method we have highlighted the optimization of the total weight of the truss. So by using such weight the optimal design can be made for the improved truss development. For 10 bars the parameters of design should be in the following range: density is 0.1lb, length is 19.9 in, area is 2.5 in^2. For 25 bars the parameters of design should be in the following range: density is 0.1lb, length is 7.22 in, area is 1 in^2. These are the parameters for the single bar in each cases and this can be used in the construction of truss for the work.

In our proposed method Cuckoo search provides the lowest weight in the lowest iteration and hence the computational time is also reduced in our proposed technique. From the comparison study of the performance of CS with GAs and ABC, we know that Cuckoo Search in combination with Levy's flights is very efficient and proves to be superior for almost all the test problems. This is partly due to the fact that there are fewer parameters to be fine-tuned and new search is introduced in CS than in ABC and genetic algorithms.

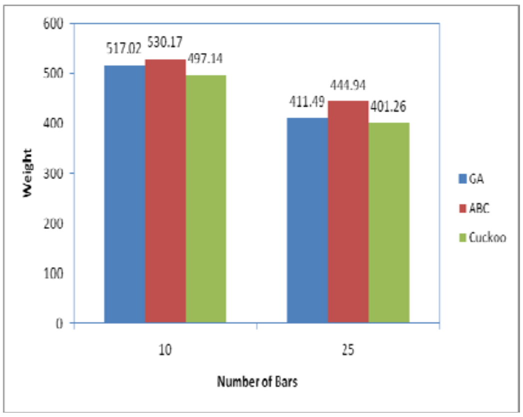

Fig. 3 Comparison of based on weight for 10 and 25 bars

Fig. 3 represents the graph comparison of our proposed work with GA and ABC with respective to their weight. In this graph 3 different bars (10 and 25) have been used. In comparison it is clear that cuckoo search provides lowest weight than other algorithms. Also the above graph indicated that when the bars increases the weight decreases.

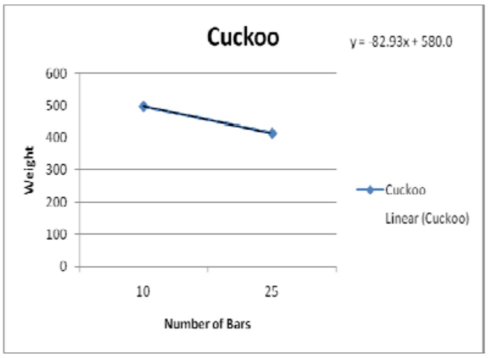

Fig. 4 Variation of weight with bars

Fig. 4 represents the variation of weight of bars with varying in the number of bars. In above graph horizontal axis represents the number of bars and the vertical axis corresponds to the weight obtained from the proposed work. The graph explains a decline in the weight variation as the number of bar increases. The equation $y= -82.93x+580.0$ indicates the variation of the bars with weight and the negative sign indicates the order of decreasing in the weight as the number of bars increases. By changing the number of bars the weight changes based on their cross sectional area and length. As the material used for the construction of the truss remains the same hence the density of the material remains constant.

III. Conclusion

Cuckoo search algorithm via Levy's flights is applied to optimum weight of truss structures. From the CS algorithm one can observe essentially three major facts: selection of the best, exploitation by local random walk, and exploration by randomization via Levy's flights globally. In this proposed technique, the replaced weight of the bars has been optimized so that the weight of the total construction can be reduced. Since the material used for the construction of the total truss is reduced the total cost of the construction is also reduced. This work also highlights on the reduction of number of analyses and computational time. For large search spaces the Levy's flights are usually more efficient. Hence in our proposed method we have compared the cuckoo search algorithm with GA and ABC to prove that our proposed method provides best results in lowering the weight of the total truss and also in lowering the number of analyses. The proposed algorithm can be applied to many combinatorial optimization problems, stochastic problems, dynamic problems in real variables, and in any areas where supervision is not required.

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