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Optimal design of truss structures with frequency constraints using improved differential evolution algorithm based on an adaptive mutation scheme

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ABSTRACT

The paper presents an improved differential evolution (IDE) and its application for solving shape and size optimization problems of truss structures with frequency constraints. The improvements are made in mutation and selection phases but mainly focused on the mutation phase. In the mutation phase of the IDE, a new selection scheme is proposed by using multi-mutation operators that adaptively employ all four popular mutation operators, including "rand/1," "rand/2," "best/1," and "best/2" for selecting target vectors in population. This new scheme helps maintain effectively the balance between the global exploration and local exploitation abilities for searching process of the DE. In the selection phase of the IDE, an elitist selection technique that helps save good individuals for the next generation is suggested to replace traditional selection technique of the original DE. The suggested technique can help increase the convergence rate of the IDE. The efficiency and robustness of the IDE are demonstrated through five benchmark problems. Numerical results show that in most of the cases considered, the optimum design obtained by the IDE and DE are nearly the same and they are better than those gained by some other well-known methods in the literature. However, the IDE is much better than the DE in terms of the computational cost.

1. Introduction

The aim of shape and size optimization of truss structures with frequency constraints is to minimize the whole weight of the structures while frequency constraints must be satisfied. For this kind of optimization problems, two types of design variables, including nodal coordinates and the element areas, are considered. The frequency constraints play a vital role for avoiding resonance phenomenon of structures [1], but in mathematical aspect, it is not easy to solve because of their highly nonlinear, non-convex, and implicit function properties. Therefore, despite of being introduced by Bellagamba and Yang in 1981 [2], the structural optimization with frequency constraints still has a lot of rooms for improvement and attracts certain attention from researchers.

In general, there are two approaches for dealing with structural optimization problems with frequency constraints. They include the gradient-based mathematical programming methods and the population-based meta-heuristic algorithms. Due to the barriers like highly nonlinear, non-convex, and implicit with respect to the design variables, the gradient-based optimization methods are often hard to address this type of optimization problem since they require gradient information of frequency with respect to design variables and depend too much on choosing initial points to successfully obtain a global optimum solution. On the contrary, thanks to global search abilities without using gradient information, the population-based meta-heuristic algorithms have shown to be efficient methods for tackling this type of problem. Some of typical research in this direction can be mentioned as follows. Yang et al. [3] employed an evolutionary structural optimization (ESO) method and a bidirectional ESO method (BESO) to solve structural topology optimization problems subjected to frequency constraints. Xu et al. [4] used an algorithm based on the topology group concept to solve the truss optimization under natural frequency constraints, stress, displacement, Euler buckling, and multiple loading conditions. Lingyun et al. [5] enhanced exploitation capability and convergence speed of a genetic algorithm (GA) to find the optimum solution of shape and size optimization problems of truss structures with multiple frequency constraints. Gomes [6] first exploited a well-known meta-heuristic algorithm, particle swarm optimization (PSO), for truss optimization with dynamic constraints.

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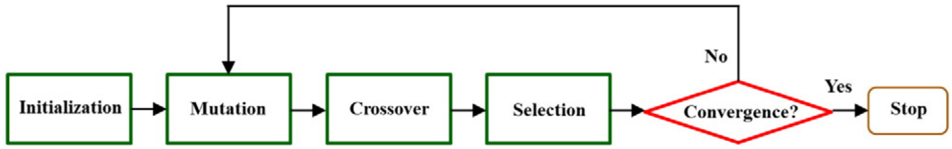

Fig. 1. Flowchart of the DE algorithm.

Miguel and Fadel Miguel [7] first used the harmony search (HS) and firefly algorithm (FA) to solve truss shape and size optimization problems with multiple frequency constraints. Zuo et al. [8] presented a hybrid algorithm that combines an optimality criterion (OC) method and GA for truss optimization restricted with frequency constraints. Khatibinia and Naseralavi [9] proposed an orthogonal multi-gravitational search algorithm (OMGSA) for shape and size optimization of truss structures with multiple frequency constraints. This type of problem was also solved by Kaveh et al. [10–14] with many different algorithms.

Among the variety of population-based meta-heuristic algorithms (e.g., particle swarm optimization (PSO) [15], artificial bee colony (ABC) [16], and cuckoo search (CS) [17], etc.), the differential evolution (DE) algorithm, first proposed by Storn and Price [18], has been proven to be one of the most promising methods when it was tested efficiently for over fifty different benchmark functions [19]. It also has been successfully applied and developed for numerous problems in many different fields such as communication [20], pattern recognition [21], mechanical engineering [22–27], structural health monitoring [28,29], artificial neural network training [21,30], and so forth. Nevertheless, it is still limited in solving structural design optimization problems under frequency constraints. In addition, similar to many other meta-heuristic algorithms, the main limit of the DE also concerns the high computational cost [31–33].

The paper hence tries to fill in the above research gaps by proposing an effectively improved differential evolution (IDE) and its application for solving shape and size optimization problems of truss structures with multiple frequency constraints. The improvements are made in mutation and selection phases but mainly focused on the mutation phase. In the mutation phase of the IDE, a new selection scheme is proposed by using multi-mutation operators, which adaptively employ all four popular mutation operators, including "rand/1," "rand/2," "best/1," and "best/2" for selecting target vectors in population. This new scheme helps maintain effectively the balance between the global exploration and local exploitation abilities for searching process of the DE. In the selection phase of the IDE, an elitist selection technique that helps save good individuals for the next generation is suggested to replace traditional selection technique of the original DE. The suggested technique can help increase the convergence rate of the DE and hence also help reduce significantly the computational cost. The IDE is then applied to solve five benchmark shape and size optimization problems of truss structures with multiple frequency constraints.

The rest of the paper is organized as follows. The mathematical model of the shape and size optimization problems of truss structures with multiple frequency constraints is briefly introduced in Section 2. The basic differential evolution algorithm is then briefly presented in Section 3. The improved differential evolution (IDE) algorithm is then described in detail in Section 4. Next, five numerical examples of the shape and size optimization problems of truss structures with multiple frequency constraints are investigated in Section 5. Finally, some concluding remarks are made in Section 6.

2. The truss optimization with frequency constraints

The objective of the truss optimization problem with frequency constraints is to minimize the weight of a truss structure, but still satisfies frequency constraints. Design variables are cross-sectional areas of bars and/or the coordinates of the truss nodes. Each design variable is confined within an acceptable region. The structural topology is pre-defined and kept fixed during the optimal design process. The mathematical model of the optimization problem can be described as follows:

$$\begin{aligned}&\text{Minimize} \quad \text{Weight}(\mathbf{A},\mathbf{x}) = \sum_{i=1}^{n} L_i(x_i)\rho_i A_i, \quad i = 1, 2, \dots, n\\ &\text{subjected to} \quad \omega_j \ge \omega_j^* \quad \text{for some natural frequencies } j\\ &\qquad \omega_k \le \omega_k^* \quad \text{for some natural frequencies } k\\ &\qquad A_l^{\text{low}} \le A_l \le A_l^{\text{up}} \quad \text{for some bar cross-sectional areas } l\\ &\qquad x_m^{\text{low}} \le x_m \le x_m^{\text{up}} \quad \text{for some node coordinates } m\end{aligned} \tag{1}$$

where $\mathbf{A}$ and $\mathbf{x}$ are the design variable vectors, including the cross-sectional areas of bars and the nodal coordinates, respectively; Weight($\mathbf{A}$,$\mathbf{x}$) is the weight of the whole truss structure; ρ_i and L_i denote the material density and the length of the ith member, respectively; n is the total number of bars in the truss; ω_j is the jth natural frequency of the structure and ω_j^* is its lower bound; ω_k is the kth natural frequency of the structure and ω_k^* is its upper bound; A_l^{low} and A_l^{up} are the lower

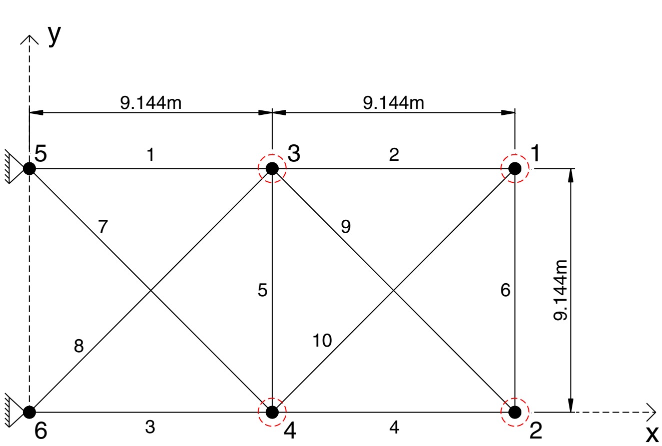

Fig. 2. Model of the 10-bar planar truss structure.

Table 1
Data for the 10-bar planar truss structure.

Parameters (unit)	Value
Modulus of elasticity E (N/m^2)	6.89×10^{10}
Material density ρ (kg/m^3)	2770
Added mass (kg)	454
Allowable range of cross sections (m^2)	$0.645 \times 10^{-4} \le A \le 50 \times 10^{-4}$
Constraints on first three frequencies (Hz)	$\omega_1 \ge 7$, $\omega_2 \ge 15$, $\omega_3 \ge 20$