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Direct optimization of uncertain structures based on degree of interval constraint violation

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ABSTRACT

A constrained interval optimization model is proposed for the optimization of uncertain structures with their mechanical performance indices described as the objective and constraint functions of the design vector and interval uncertain parameters. Present indirect approaches for solving such interval optimization models by converting them into deterministic ones will result in the loss of uncertainty information and deviate from the original intention of realistically modeling engineering optimization problems. To overcome these shortcomings, a novel optimization algorithm is proposed for directly solving the nonlinear constrained interval optimization models based on a novel concept of the degree of interval constraint violation (DICV) and the DICV-based preferential guidelines. A nested genetic algorithm (GA) is developed to realize the direct interval ranking of various design vectors. The outer layer GA locates the optimal solution based on direct interval ranking. The inner layer GAs integrated with Kriging technique compute the intervals of the mechanical performance indices of every design vector in the current population of the outer layer GA. The validity and superiority of the proposed direct interval optimization algorithm was verified by three numerical examples. Finally, the proposed direct interval optimization method was applied to the optimization of the cone ring fixture with uncertain material properties in a large turbo generator aimed at moving its natural frequencies away from the exciting one. The results demonstrated its feasibility and effectiveness in optimizing practical engineering structures under uncertainties.

1. Introduction

In the design of engineering structures, it is often necessary to optimize their key dimension parameters to achieve excellent mechanical properties. To ensure the reliability and robustness of the optimized parameter schemes for engineering structures, the uncertainties inherent in their material properties, manufacturing errors, loading conditions and so on should be considered in the mathematical modeling of the structural optimization problems because these uncertainties will result in the fluctuations of their mechanical properties [1,2]. The fuzzy set method [3,4] and probabilistic method [5] are often utilized to model the uncertainties in structural optimization. However, it is often difficult and expensive to specify a precise probability distribution or membership function for an uncertain parameter in engineering practice. And even small deviations from the real distribution for an uncertain parameter may lead to large errors in the computed probability failure to meet structural requirements [6–8]. In order to overcome the shortcomings of fuzzy and probabilistic methods for modeling uncertainties, scholars began their research work on non-probabilistic modeling of uncertainties [9–11]. In this situation, the structural optimization based on interval theory have recently attracted great interest from scholars all over the world due to the fact that only the upper and lower bounds of the uncertain parameters are required for the construction of interval optimization models [12–15]. For example, Elishakoff et al. [16–18] have carried out a lot of fruitful research work in this field. They proposed a design approach for structural optimization with uncertain but bounded parameters and formulated the problem of identifying the worst responses of a structure with respect to the uncertain parameters as an anti-optimization problem (namely, the inner layer optimization in this paper), which resulted in a two-level optimization problem. They replaced the anti-optimization for searching the worst combination of uncertain parameters by systematic searches along the vertices of the uncertain domain in optimizing truss structures. Faria et al. [19–21] later applied the anti-optimization technique to the optimization of composite structures considering load uncertainties.

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Interval optimization algorithms are of vital importance to realize the structural optimization based on interval model. Over the past decades, intensive research efforts have been focused on interval linear programming. Ishibuchi and Tanaka [22] investigated the linear programming problem with interval coefficients in the objective function. They proposed a definition of interval order relation and converted the interval optimization problem into a deterministic multiobjective one with crisp objective functions. Tong [23] investigated the linear programming problem with both the coefficients of objective and constraints being interval numbers, and obtained the possible interval of the solution by taking the maximum and minimum value range inequalities as constraint conditions. Huang et al. [24] proposed a two-step method (TSM) for solving the interval linear programming problems, which allowed the uncertain information to be directly communicated into the optimization process and resulting solutions such that decision alternatives could be generated through the interpretation of interval solutions. However, part of the optimum solutions obtained by TSM may go beyond the decision space in some cases. To avoid this shortcoming, Wang and Huang [25] proposed an improved method by introducing extra constraints in the solution process. Inuiguchi and Sakawa [26,27] proposed the minimax regret solution to linear programming problems with an interval objective function, which were further extended to the multiobjective linear programming problems with interval objective functions coefficients by Rivaz and Yaghoobi [28]. Averbakh and Lebedv [29] proved that the computational complexity of minimax regret linear programming was NP-hard. Sengupta et al. [30] converted an interval linear programming problem into a deterministic one based on a satisfactory crisp equivalent system of an inequality constraint with interval coefficients, and then solved the problem after conversion by conventional linear programming techniques. Lai et al. [31] defined the non-inferior solutions to interval linear programming models based on two interval order relations. Oliveira and Antunes [32] conducted an illustrated review of multiobjective linear programming models with interval coefficients.

In the above linear interval programming methods, the objective and constraint functions are given in analytical forms. However, the objective and constraints corresponding to the mechanical performance indices are often nonlinear for most of the structural optimization problems, the values of which are usually computed by numerical simulations. Hence, the nonlinear interval programming approaches developed in recent years have exhibited much more attractive prospect for the optimization of uncertain structures. Lombard and Haftka [33] proposed a cycle-based method alternating between optimization and anti-optimization to solve the two-level optimization problem, in which the inner layer anti-optimization problem should be solved many times at each iterative step of the outer layer design optimization. Gurav et al. [34] further proposed an enhanced cycle-based method that utilized the parallel computation technique to reduce the computational cost in the inner layer anti-optimization. Although the idea of the cycle-based method is simple and it is simple to implement, it cannot rapidly converge when the anti-optimal solution strongly or nonlinearly depends on the design variables. Moreover, the cycle-based approaches cannot handle the interval nonlinear optimization problems with both objective and constraints being functions of design variables and uncertain parameters. Hu and Wang [35,36] proposed new arithmetic and order relations for interval numbers that had the property of comparability, based on which they presented two methods for solving nonlinear programming problems with interval objective functions. One method firstly converted a nonlinear interval programming problem into two traditional nonlinear programming problems and solved them sequentially while the other firstly determined the set of feasible solutions and then obtained the optimal solution based on the comparison of their objective values. However, their approaches are designed only for problems with analytical objective and constraint functions. Chen and Wu [37] proposed an interval optimization method for optimizing the dynamic responses of uncertain structures with natural frequency constraints, which firstly transformed the interval optimization model into a deterministic one based on the first order Taylor expansion and then solved the deterministic model by traditional nonlinear optimization algorithm. However, their approach is limited to the cases with interval parameters of small uncertainty level since it ignores the higher order terms in Taylor expansion. Jiang et al. [38–42] proposed a series of algorithms for solving nonlinear interval optimization problems. They firstly transformed the interval objective and constraint functions into deterministic ones based on possibility degree of interval, and further transformed them into unconstrained single-objective deterministic optimization problems by weighting and penalty function method, which were then solved by various nonlinear programming algorithms. Different from the researches that treat every uncertain parameter as an isolated interval, Jiang et al. [43] also proposed a nonlinear interval programming method that could handle uncertain optimization problems when there were dependencies among interval variables. They described the uncertain domain as a multidimensional parallelepiped interval model with the single-variable uncertainty depicted as a marginal interval while the degree of dependencies among the interval variables depicted as correlation angles and correlation coefficients. In the solution process, they still firstly converted the interval model into a deterministic one based on possibility degree of interval, and then solved the resulting deterministic model by iterative algorithm. Li et al. [44] proposed an interval multi-objective optimization method for structures based on adaptive Kriging approximations, which transformed the interval model into a corresponding nested deterministic multiobjective one and solved the deterministic model based on non-dominated sorting genetic algorithm (NSGA2) and adaptive Krigings. To save the computational costs in the interval optimization of structures, Elishakoff et al. [45–47] developed a series of inner layer anti-optimization approaches based on interval analysis. In order to reduce or eliminate the overestimations due to the so-called dependency phenomenon arising in the classical interval analysis, they introduced the parameterized interval analysis and the improved interval analysis via Extra Unitary Interval, which could efficiently solve the set of governing algebraic interval equations in statics [48]. Cheng et al. [49] proposed an interval multiobjective optimization approach of structures based on radial basis function, interval analysis and NSGA2, which transformed the interval multiobjective optimization model into a deterministic one and eliminated the inner layer optimization based on interval analysis. Wu et al. [50] combined the Taylor inclusion function and interval bisection algorithm to eliminate the inner layer optimization for computing the interval bounds of objective and constraint functions, which was proved to be superior to conventional interval analysis for the interval optimization of vehicle suspensions.

As can be seen from the above literature review, most of the previous approaches for solving the nonlinear interval optimization model are indirect approaches. Specifically, they firstly convert interval constraints into deterministic ones by prescribing their acceptable possibility levels, and then solve the resulting model by deterministic optimization algorithms [38–44,49]. However, the determination of acceptable possibility levels for constraints in the model conversion procedure is usually subjective and optional. And different acceptable possibility levels will result in different solutions. On the other hand, the process of converting an interval optimization problem into a deterministic one will