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Robust optimization of uncertain structures based on normalized violation degree of interval constraint

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ABSTRACT

In order to improve the mechanical properties of a structure with uncertain but bounded parameters, a constrained interval robust optimization model is proposed with the center and halfwidth of its most important mechanical performance index described as objectives and the other performance indices described as constraints. The conventional indirect approaches for solving the interval optimization model will result in different optimal solutions when prescribing different satisfactory degrees of interval constraints and also deviates from the original intention of modeling the optimization problem based on interval theory. To overcome the shortcomings of indirect interval optimization approaches, a novel concept of the normalized violation degree of interval constraint (NVDIC) and the NVDIC-based preferential guidelines are proposed for directly sorting different design vectors. A direct interval robust optimization algorithm is proposed, which integrates Kriging models with inner layer genetic algorithms (GAs) to compute the interval bounds of the mechanical performance indices of various design vectors, and realizes the direct sorting of different design vectors by the outer layer non-dominated sorting genetic algorithm (NSGA) according to the NVDIC-based preferential guidelines. The validity of the proposed direct interval robust optimization algorithm is verified by a numeric example, the superiority of which to the conventional indirect one is discussed in detail. Finally, the robust optimization of a press slider with uncertain material properties demonstrates the feasibility and validity of the proposed method in engineering.

1. Introduction

There often exist many uncertainties in the manufacture and assembly of engineering structures, such as material properties, dimensional tolerances, and boundary conditions. These uncertainties will result in the fluctuations of the structures' mechanical properties. The optimal solutions to the traditional deterministic models that neglect these uncertainties may become infeasible in engineering practice. Hence it is necessary and important to consider these uncertainties in modeling the optimization problems of the structures and develop corresponding uncertain optimization algorithms in order to obtain solutions applicable in engineering practice [1–4]. The uncertainty-based design methods mainly include two categories, namely the robust design optimization [5–10] and reliability-based design optimization [11–21]. The former aims at improving the robustness of a structure and reducing the sensitivities of its mechanical properties to the variation of design variables and noise factors while the latter aims at enhancing the reliability of a structure and reducing the chance of function failure under potential critical conditions. The work presented here contributes to the former and the following literature review mainly focuses on the former.

Most of the present researches on the robust design optimization regarded that the probability distributions of uncertain factors were known or could be obtained. For instance, Chen et al. [22] developed a general robust design procedure by integrating the response surface methodology with the comprise decision support problem and got the derivation of the mean and variance of target response by second-order expansions, but the method is not appropriate for large-scale problems because of its huge computational cost. Yu and Ishii [23] took the correlation between uncertain factors into consideration and utilized Taylor method to get the approximation of the mean and variance with covariance items. They also proposed a zero-order fractional quadrature factorial method to get the robust solution. Hwang and Park [24] proposed a three-step robust design method with the introduction of a new robustness index. Lee et al. [25,26] compared the precision and efficiency of the univariate dimension reduction method (DRM), performance moment integration (PMI) method and percentile difference method (PDM) for estimating mean and variance, and concluded that DRM was effective for small number

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of random variables whereas PMI was effective for relatively large number of random variables. Tang and Périaux [27] proposed a robust optimization method that could locate Pareto and Nash equilibrium solutions of good performance and stability by combining the Pareto and Nash game strategies with the adjoint method. Lee and Park [28] investigated the effects of design tolerances on the objective and constraint functions. They utilized the weighting method to transform the mean and variance into a single objective and added up the constraint's variance into constraint function as a penalty term. Beer and Liebscher [8] proposed a novel numerical procedure for designing robust structures under uncertainty, which can be coupled with fuzzy, random or fuzzy random computational model for static or dynamic structural analysis. They firstly determined several permissible design alternatives by cluster analysis methods, and then formulated a discrete three-criteria optimization problem that was focused on maximum structural robustness and included a safety component. The global robustness of the design alternatives was defined as the ratio between the entropy of input parameters and that of structural responses. Luo and Du [29] regarded that random variables in engineering were practically not normally distributed and tried to describe them as bounded random variables. The above probabilistic robust optimization approaches require the distributions of uncertain factors to be obtained at first. However, it is often difficult and computationally expensive to obtain the probabilistic distributions of most uncertain factors in engineering.

To realize the robust optimization in the absence of the distributed information of uncertainties, several non-probabilistic robust optimization approaches have been developed in recent decades. Balling et al. [30] proposed the worst case analysis method to predict the variation of objective and constraint functions, and utilized a reversed method to get the optimization result. Zhu and Ting [31] proposed the concept of sensitivity distribution to describe the influence of uncertain factors on system performance. They utilized an ellipse and a rectangle to respectively represent the feasible region of target performance and the variation range of uncertain factors, and evaluated the robustness by comparing the shape and size of two regions. But their method will be very complex when there are a large number of parameters. Siddiqui et al. [9] proposed a modified Benders decomposition method for efficient robust optimization under interval uncertainty. But their method can only obtain an approximate locally optimal robust solution to general nonlinear optimization problems. Moreover, present researches on non-probabilistic robust optimization approaches rarely devote to the development of direct optimization algorithms for solving the non-probabilistic models and usually implement indirect optimization processes. For instance, they usually transform the constrained interval optimization models into deterministic ones by prescribing the satisfactory degrees of interval constraints, and further transform the constrained multiobjective deterministic optimization models into unconstrained single-objective ones by weighting and penalty function methods, which are then solved by simple deterministic optimization algorithms [32–36]. The optimization results obtained by such kind of indirect approaches are subjective and uncertain since different satisfactory degrees of interval constraints as well as different weighting and penalty factors will result in different optimal solutions. Additionally, the computation of the probabilities that interval constraints are satisfied at the prescribed satisfactory degrees is implemented by regarding interval variables as uniformly distributed random variables, which also deviates from the original intention of modeling the optimization problem based on interval theory in the absence of the probabilistic information of uncertain factors. To overcome the shortcomings of indirect approaches, we have previously proposed a direct algorithm for solving the single-objective interval optimization models of uncertain structures by introducing the concept of the degree of interval constraint violation (DICV) [37]. However, both the objective and constraint functions of the optimization models investigated here are more complex than those in our previous work due to the robust requirement and constraint diversity of uncertain structures considered here. At the same time, the computation of the total DICV of a design vector by the simple addition of DICVs corresponding to different constraint functions may not realistically reflect the violation degree of a constraint performance index of small magnitude when there is a constraint performance index of large magnitude because the DICV in our previous work is a dimensional quantity. Moreover, the preferential guide for ranking feasible design vectors according to Hu's "center first halfwidth next" interval order relation in our previous work is obviously not applicable for the ranking of feasible design vectors for the robust optimization model since the center and halfwidth of objective performance index should be regarded as equally important. Additionally, the computation of DICV corresponding to a constraint function is somewhat complex since different formula should be chosen according to the comparison results of the constraint performance index with given interval constant based on the "center first halfwidth next" rules. Consequently, the direct solution algorithm in our previous work is not appropriate for solving the interval robust optimization problems investigated here.

To overcome the above-mentioned limitations of the present robust optimization approaches and realize direct robust optimization of uncertain structures with interval parameters, a direct interval robust optimization method is proposed for optimizing a structure with uncertain parameters. Firstly, a constrained interval robust optimization model is constructed, which utilizes the center and halfwidth of the most important performance index of the uncertain structure as objectives and describes the other performance indices as constraint functions. Secondly, a novel concept of the normalized violation degree of interval constraint (NVDIC) is proposed for evaluating the feasibility of a design vector to the effect that the possible neglect of constraint performance indices of small magnitudes is avoided. The unified formulae for efficiently computing the NVDIC of various constraint functions are also put forward. Then the preferential guidelines based on NVDIC are put forward for sorting various design vectors and locating the robust optimal design vector by regarding the center and halfwidth of the objective performance indices as equally important. Thirdly, a direct interval robust optimization algorithm is developed to locate the optimal solution to the constrained interval robust optimization model, which can avoid the subjectivity in prescribing the satisfactory degree(s) of interval constraint(s) in the indirect interval optimization approaches and ensure the robustness of the optimal solution. Specifically, it is a nested optimization algorithm that integrates Kriging models with a series of inner layer genetic algorithms (GAs) to compute the interval bounds of the mechanical performance indices of a design vector under the uncertainties and realizes the direct sorting of various design vectors according to the NVDIC-based preferential guidelines in the outer layer non-dominated sorting genetic algorithm (NSGA).

The rest of this paper is organized as follows. The constrained interval robust optimization model of an uncertain structure is put forward in Section 2. The novel concept of NVDIC for evaluating the feasibility of a design vector and the NVDIC-based preferential guidelines for directly sorting various design vectors are proposed in Section 3. The direct interval robust optimization algorithm integrating Kriging models, inner layer GAs and outer layer NSGA is proposed in Section 4, the validity and superiority of which is verified by a numeric example. Then the proposed approach is applied to the robust optimization of a press slider with uncertain material properties in Section 5, a detailed