Mechanical Systems and Signal Processing 102 (2018) 329–345

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

journal homepage: www.elsevier.com/locate/ymssp

Possibility-based robust design optimization for the structural-acoustic system with fuzzy parameters

Hui Yin, Dejie Yu *, Shengwen Yin, Baizhan Xia

State Key Laboratory of Advanced Design and Manufacturing for Vehicle Body, Hunan University, Changsha, Hunan 410082, People's Republic of China

ARTICLE INFO

Article history:
Received 31 March 2017
Received in revised form 7 August 2017
Accepted 23 September 2017

Keywords:
Structural-acoustic system
Fuzzy parameters
Fuzzy expectation and entropy
Possibility
Robust design
Chebyshev polynomials

ABSTRACT

The conventional engineering optimization problems considering uncertainties are based on the probabilistic model. However, the probabilistic model may be unavailable because of the lack of sufficient objective information to construct the precise probability distribution of uncertainties. This paper proposes a possibility-based robust design optimization (PBRDO) framework for the uncertain structural-acoustic system based on the fuzzy set model, which can be constructed by expert opinions. The objective of robust design is to optimize the expectation and variability of system performance with respect to uncertainties simultaneously. In the proposed PBRDO, the entropy of the fuzzy system response is used as the variability index; the weighted sum of the entropy and expectation of the fuzzy response is used as the objective function, and the constraints are established in the possibility context. The computations for the constraints and objective function of PBRDO are a triple-loop and a double-loop nested problem, respectively, whose computational costs are considerable. To improve the computational efficiency, the target performance approach is introduced to transform the calculation of the constraints into a double-loop nested problem. To further improve the computational efficiency, a Chebyshev fuzzy method (CFM) based on the Chebyshev polynomials is proposed to estimate the objective function, and the Chebyshev interval method (CIM) is introduced to estimate the constraints, thereby the optimization problem is transformed into a single-loop one. Numerical results on a shell structural-acoustic system verify the effectiveness and feasibility of the proposed methods.

1. Introduction

In the last few decades, extensive researches have been made on the engineering analysis and design optimization. Conventionally, the design optimization is implemented under deterministic models. However, uncertainties caused by manufacturing or construction tolerances, external loading fluctuations and unpredictable environment factors inevitably exist in practical engineering systems, and these uncertainties are likely to cause remarkable variability in system performance, thus they should be properly handled in system design optimization. The system design optimization problem accounting for uncertainties was firstly explored by Dantzig [1]. Up to now, two important types of uncertain optimization frameworks have been developed, namely the reliability-based design optimization (RBDO) [2] and the robust design optimization (RDO) [3]. In RBDO, the system performance is optimized under reliability constraints with predefined failure

* Corresponding author.
E-mail address: djyu@hnu.edu.cn (D. Yu).

https://doi.org/10.1016/j.ymssp.2017.09.037
0888-3270/

chance; while RDO aims at optimizing the expectation and variability of system performance with respect to uncertainties simultaneously.

Before performing the uncertainty-based optimization, one should select a way to describe the uncertainties. The probabilistic model is the prior choice if sufficient objective information about the uncertainties is available to define the precise probability distribution of the uncertain parameters. RBDO under the probabilistic model has been applied to varieties of engineering fields and achieved significant progress. For example, Frangopol and Maute targeted the problem of RBDO for life-cycle engineering of civil and aerospace structures with probabilistic parameters [4]; Kharmanda combined RBDO with stochastic topology optimization for structures [5]; the neural networks (NN) and the Monte Carlo method were used to handle RBDO problems for large-scale systems with probabilistic parameters in [6]; approximate methods were developed to efficiently estimate the objective functions and the reliability of constraints in RBDO [7–10]. Since Taguchi's research work on quality control in 1984 [11], RDO under probabilistic model has also been applied to different engineering fields and developed significantly. For instance, Mulvey et al. studied the robust optimization of large-scale systems with random parameters [12]; Allen et al. studied the robust design for multi-scale and multidisciplinary applications under probabilistic model [13]; Yao et al. discussed the RDO for aerospace vehicles based on probability theory [14]; RDO was combined with the stochastic topology optimization for structures with different sources of uncertainties [15–17]; approximate methods were also developed to efficiently deal with the robust optimization of practical engineering designs [18–20]. To improve the robustness of system performance subject to reliability constraints, RDO and RBDO under probabilistic model were merged, which yields the reliability-based robust design optimization (RBRDO) [21–23]. Given that RBRDO can handle the robust optimization and the reliability constraints simultaneously, it provides a more comprehensive optimization framework for uncertain engineering system.

Although uncertain optimization under probabilistic model has been well established, it has an inescapable drawback—it is not always possible to obtain sufficient objective information to precisely define the probability distributions of uncertain parameters in engineering practice, thus using the probabilistic model to describe the uncertain parameters is infeasible sometimes. Under such circumstances, the non-probabilistic model, such as the convex model (including the interval model) [24,25] and the fuzzy set model [26,27], can be used to describe the uncertainties in the system to be optimized. The convex model can be constructed once that the bounds of uncertainties are well defined, and there is no need to know the information on the occurrence frequency of the uncertainties, thus only a small number of samples is required. For the uncertain optimization under convex model, Kang et al. developed a non-probabilistic reliability-based design optimization (NRBDO) framework [28] and a RDO framework [29] for structures with bounded uncertainties. The fuzzy set model was developed for dealing with human epistemic uncertainties, and it can be constructed on the basis of available expert opinions, which are relatively easier to be obtained than a large amount of objective information. Unlike the probabilistic reliability analysis, the fuzzy reliability analysis for uncertain systems is usually performed in the context of possibility theory [30]. Cai et al. [31] first introduced the fuzzy reliability analysis in the possibility context; Utkin and Gurov [32] developed a general formal approach for fuzzy reliability analysis in the possibility context. Accordingly, uncertain optimization with fuzzy constraints is generally termed as possibility-based design optimization (PBDO) [33]. Uncertain optimization under fuzzy set model have been well established and widely used by many investigators. Mourelatos and Zhou [34] proposed a unified approach addressing the inaccuracies of interval analysis and antioptimization method based on an efficient hybrid global–local optimization; Du et al. [35] proposed an inverse possibility analysis method for PBDO; Behravesh and Ebadi [36] studied the optimization of space structures with fuzzy constraints via real coded genetic algorithm; Tang et al. [37] proposed a target performance-based design approach for design optimization of structures with fuzzy constraints; Massa et al. [38] proposed a fuzzy multi-objective optimization framework for mechanical structures; Marano and Quaranta [39] proposed a fuzzy-based robust design optimization (FRDO) framework for fuzzy structures based on the expectation and entropy of fuzzy variables; Youn et al. [40] integrated PBDO with the RDO to minimize the sum of material cost and quality loss cost. In summary, as attractive supplements to the probabilistic model, both the convex model and the fuzzy set model have been frequently used in the uncertain optimization. This paper employs the fuzzy set model to describe uncertainties for the uncertain optimization.

Over the past two decades, optimization for deterministic structural-acoustic systems has been extensively studied in both academic and engineering practice [41–43]. Given that uncertainties are inevitable in practical structural-acoustic system, optimization for uncertain structural-acoustic systems has been explored recently. Wang et al. [44] studied the reliability-based optimization of uncertain structural-acoustic system with interval parameters; Xia and Yu [45] proposed an optimization technique named as optimization based on reliability and confidence interval design (O-RCID) for the optimization of the structural-acoustic system with interval probabilistic variables, in which a change-of-variable interval probabilistic perturbation method (CV-IPPM) was proposed to improve the computational efficiency of O-RCID; Xia et al. [46] studied the RBDO for the structural-acoustic system with probabilistic and interval variables, in which a hybrid perturbation random moment method (HPRMM) and a hybrid perturbation inverse mapping method (HPIMM) were proposed to improve the computational efficiency of RBDO. Up to now, optimization of uncertain structural-acoustic system is mainly focused on the interval model and the probabilistic model, while the fuzzy set model has not yet been taken into account. However, considering the advantage of fuzzy set model in modeling uncertainties, it may be of great significance to investigate its use in the optimization of uncertain structural-acoustic system.

In this paper, a new formulation of possibility-based robust design optimization (PBRDO) is proposed for the structural-acoustic system with fuzzy parameters. In the proposed PBRDO, the entropy of the fuzzy response is used as the variability