Mechanical Systems and Signal Processing 115 (2019) 524–544

Contents lists available at ScienceDirect

Mechanical Systems and Signal Processing

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

Hybrid interval and random analysis for structural-acoustic systems including periodical composites and multi-scale bounded hybrid uncertain parameters

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ARTICLE INFO

Article history:
Received 14 February 2018
Received in revised form 4 May 2018
Accepted 11 June 2018

Keywords:
Gegenbauer polynomials
Structural-acoustic system
Homogenization method
Periodical composites
Bounded hybrid uncertain model

ABSTRACT

For the response analysis of periodical composite structural–acoustic systems with multi-scale uncertain-but-bounded parameters, a bounded hybrid uncertain model is introduced, in which the interval variables and the bounded random variables exist simultaneously. In the periodical composite structural–acoustic system, the equivalent macro constitutive matrix and average mass density of the microstructure are calculated through the homogenization method. On the basis of the conventional first-order Taylor series expansion, a homogenization-based hybrid stochastic interval perturbation method (HHSIPM) is developed for the prediction of periodical composite structural–acoustic systems with multi-scale bounded hybrid uncertain parameters. By incorporating the Gegenbauer polynomial approximation theory into the homogenization-based finite element method, a homogenization-based Gegenbauer polynomial expansion method (HGPEM) is also proposed to calculate the bounds of expectation and variance of the sound pressure response. Numerical examples of a hexahedral box and an automobile passenger compartment are given to investigate the effectiveness of the HHSIPM and HGPEM for the prediction of periodical composite structural–acoustic systems with multi-scale bounded hybrid uncertain parameters.

1. Introduction

In recent years, composite materials have been widely applied in the military industry and construction industry, especially, in the vehicular and aviation industry owing to its lightweight, high strength and tenacity features. However, when excited by a harmonic force, the flexible and lightweight composite panels are vulnerable to vibration and can radiate noise into passenger compartment. In particular, when the harmonic exciting frequency is close to the inherent frequency of composite panels or the acoustic cavity of the passenger compartment, the resonant noise generated by the composite panels is beyond sufferance. Therefore, conducting the vibro-acoustic analysis of composite structural-acoustic systems is very worthwhile and meaningful.

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https://doi.org/10.1016/j.ymssp.2018.06.016
0888-3270/

With the rapid development of researches on the analyses of structural-acoustic systems, a lot of numerical approaches have been proposed. The coupled finite element method/finite element method (FEM/FEM) is the most commonly used one among these approaches for structural-acoustic systems in engineering practice. In the coupled FEM/ FEM, both the structure domain and the fluid domain are simulated by FEM models. However, the key point of solving the composite structural-acoustic problem is to analyze the composite material firstly at micro-scale before calculating the response of the structural-acoustic system at macro-scale. Generally, a composite material has a complicated microstructure and various constituents, which can lead to the inherent characteristics of composite materials, such as strong heterogeneity and anisotropy [1,2]. Through the homogenization method which is based on an asymptotic expansion of the governing equations, the effective parameters of the heterogeneous composite material can usually be induced [3–5]. In this way, the heterogeneous medium is transformed into an equivalent material model which is energetically equivalent to the heterogeneous medium. By integrating the homogenization method with the coupled FEM/FEM, the homogenization-based finite element method (HFEM) is proposed for the prediction of periodical composite structural–acoustic systems [6]. In the HFEM, the bi-material solid isotropic material with penalization model is employed to describe the material distribution of the microstructure [7].

Traditional numerical methods for the dynamic analysis of the vibration and noise issues are mainly based on deterministic geometric, material and physical parameters. However, uncertainties related to these parameters are unavoidable in practical engineering due to the effects of aggressive environment factors, inevitable manufacturing errors and incomplete knowledge [8–10]. The analysis results may be unreliable without considering those uncertainties involved in the system. In this context, increasing attention has been gained on the uncertain analysis of structural-acoustic systems in recent years. Until now, Xia et al. have developed numerical approaches for the response analysis of structural-acoustic systems with interval parameters, hybrid random and interval parameters, and hybrid interval random parameters [11–13]. The uncertainty propagation in SEA (Statistic Energy Analysis) for structural-acoustic coupled systems with uncertain-but-bounded parameters has been investigated by Xu et al. [14]. Yin et al. have focused on the analysis of structural-acoustic systems with interval parameters at the mid-frequency range through hybrid finite element/statistic energy method [15]. A new random interval method for response analysis of structural-acoustic system with interval random variables has been proposed by Xia et al. [16]. Uncertainty analysis of a structural-acoustic problem with imprecise probabilities has been conducted by Chen et al. based on p-box representations [17]. Yin et al. have proposed a unified method for the interval and random analysis of structural-acoustic system with large uncertain-but-bounded parameters [18]. Hybrid uncertainty propagation in structural-acoustic systems has been studied by Xu et al. based on the polynomial chaos expansion and dimension-wise analysis [19]. Though a variety of researches on uncertainty analysis of the structural-acoustic system have been done, all of these aforementioned researches are limited to structures consisted of isotropic material and the considered uncertainties are confined to macro-scale. As for periodical composite structural-acoustic systems, multi-scale uncertainties exist simultaneously. At the micro-scale, the uncertainty may come from the constituent material properties of the microstructure due to manufacturing errors. The source of the uncertainties at the macro-scale is from the physical parameters of the acoustic medium and the external load resulting from the environment. Both the uncertainties from the micro-scale and the uncertainties from the macro-scale can have an effect on the frequency response of the periodical composite structural-acoustic system. Thus, multi-scale uncertainties should be considered when analyzing periodical composite structural-acoustic systems. Recently, Chen et al. have conducted the interval analysis for periodical composite structural-acoustic problem with multi-scale uncertain-but-bounded parameters based on perturbation method [6]. However, the proposed interval analysis approach inherits the drawback of the perturbation method, which limits its application in periodical composite structural-acoustic problem with small multi-scale uncertain level. Overall speaking, researches on periodical composite structural-acoustic systems with considering multi-scale uncertainties are promising but rarely reported.

To deal with the randomness, various probabilistic approaches have been developed, such as the Monte Carlo method (MCM) [20,21], the random perturbation method [22–25], the random orthogonal polynomial approximation method [26–29] and so on. However, the premise of these probabilistic approaches is that the detailed probability distribution of uncertain parameters is provided [30,31]. Unfortunately, the information to construct the probability density function (PDF) is not always sufficient or is sometimes very difficult to acquire. To overcome the shortcoming of probabilistic approaches, interval approaches provide an appropriate alternative to cope with the uncertain modeling with limited information [32]. In the interval approach, the interval variable is employed to model the uncertain parameter whose lower and upper bounds are well defined but information about its probability density functions is missing. The scanning method, the perturbation method [11,33] and the orthogonal polynomial approximation method can be used for interval analysis [14,34]. The probability approach and the interval approach are appropriate for the uncertain problems with random variables and interval variables respectively. However, sometimes the random variables and interval variables may exist simultaneously in an uncertain system. In this situation, a hybrid uncertain model is proposed by Elishakoff and Colombi [35]. In the hybrid uncertain model, the random variables are used to describe the uncertain parameters with sufficient information to determine the probability distributions, whereas, the interval variables are used to represent the uncertain parameters without sufficient information to construct the precise probability distributions. The hybrid uncertain model inherits the merits of both random model and interval model and has been widely applied in many engineering fields [36–38]. Several hybrid uncertain numerical methods are developed on the basis of the perturbation method, MCM and polynomial approximation method [12,39–41]. However, due to the manufacturing tolerance design, it has been deemed that the associated uncertain parameters are always bounded in real engineering practice. Naturally, a bounded hybrid uncertain model can be