Available online at www.sciencedirect.com
ScienceDirect
Comput. Methods Appl. Mech. Engrg. 320 (2017) 198–217
Computer methods in applied mechanics and engineering
www.elsevier.com/locate/cma

Hybrid uncertainty propagation in structural-acoustic systems based on the polynomial chaos expansion and dimension-wise analysis

Menghui Xu[a,*], Jianke Du[a], Chong Wang[b,c], Yunlong Li[c]

[a] Faculty of Mechanical Engineering & Mechanics, Ningbo University, Ningbo, Zhejiang 315211, PR China
[b] School of Civil and Environmental Engineering, Nanyang Technological University, 639798, Singapore
[c] Institute of Solid Mechanics, Beihang University, Beijing 100191, PR China

Received 29 October 2016; received in revised form 20 February 2017; accepted 21 March 2017
Available online 24 March 2017

Highlights

- The hybrid uncertainty propagation in structural-acoustic systems is accomplished.
- Requirement of small uncertainties for current methods is greatly relaxed.
- Integration with any existing numerical software without rewriting codes is simple.
- PCE-DW applies to the structural-acoustic analysis with random or interval parameters.

Abstract

Hybrid uncertainties are ubiquitous in the structural-acoustic analysis and greatly affect the behaviors of the coupled system. However, requirements of small uncertainties and rewriting simulation codes for the numerical analysis are always necessary for current methods. In this context, a non-intrusive dual-layer analysis procedure, i.e. a hybrid method of the polynomial chaos expansion and dimension-wise analysis (PCE-DW), is proposed in this paper. The PCE procedure based on the sparse grid collocation strategy is utilized to handle the random uncertainty while the DW procedure is employed to evaluate the interval bounds of statistical characteristics of the system response. The PCE-DW also applies to the structural-acoustic analysis with only random or interval parameters. The investigation of two structural-acoustic systems with hybrid uncertainties finally demonstrates the accuracy, efficiency and capability of the proposed method.

Keywords: Structural-acoustic systems; Random parameters; Interval parameters; Polynomial chaos expansion; Dimension-wise analysis

1. Introduction

The structural-acoustic analysis has undergone a rapid development in engineering during past decades due to more awareness of the NVH performance of the product with an enclosed cavity, e.g. the car, train, and airplane.

* Corresponding author.
E-mail address: xumenghui@nbu.edu.cn (M. Xu).

http://dx.doi.org/10.1016/j.cma.2017.03.026

It has been found that the noise in the enclosed cavity is significantly affected by the structure, acoustic fluid and coupled solid–fluid interface [1]. The traditional finite element method (FEM) for the structural-acoustic analysis is performed in the context of deterministic parameters. However, uncertainties associated with material properties, geometric dimensions, subjective experiences, boundary conditions and external loads are ubiquitous. The most common techniques to handle these uncertain parameters are probabilistic methods, in which uncertainties are modeled as random variables or stochastic processes. Monte Carlo (MC) method [2,3] is the most versatile one. Despite of the simplicity, it greatly suffers from the prohibitive computational cost, especially for large-scale problems. The stochastic perturbation method [4–6] is an alternative approach. However, it is efficient only for problems with small uncertainties due to the first-order Taylor series expansion of the system response with respect to (w.r.t.) the random parameters. The spectral stochastic method [7–10] is based on a series expansion to model the input–output relationship of the system, of which the polynomial chaos expansion (PCE) method [11–15] is the most popular one due to its strong mathematical basis and ability to produce functional representations of stochastic variability.

For these probabilistic methods, a large amount of statistical information on each uncertain parameter is required to guarantee the precision of its probability distribution. However, in the early stages of design, these statistical information may be insufficient [16] and subjective results could be obtained by probabilistic methods [17]. In this context, the non-probabilistic methods can be employed, which has led to elegant approaches for the interval FEM (IFEM). In IFEM, the uncertain parameters are modeled as interval variables whose lower and upper bounds are well-defined but the information about probability distributions is missing. Each IFEM can be decomposed into two individual portions in principle, i.e. the core algorithm and pre-processing procedure. The interval arithmetic approach [18–21] is an original one of the four types of core algorithms, where all deterministic algebraic operations are replaced by their interval arithmetic counterparts. However, this approach generally suffers considerably from the dependency problem and its integration with any current simulation environment for the finite element analysis (FEA) is also a challenge in real applications. The second type of core algorithm is the interval perturbation method [22–25] which is, however, effective only for problems with small interval variables. Besides the difficulty in integration with current FEA environments, an overestimation [22], interval translation effect [23], or unpredicted estimation [24,25] is always introduced by this method. If the monotonicity of the response w.r.t. uncertain parameters is guaranteed, the vertex method [26,27] can quantify uncertainties in outputs accurately. However, it is very hard to prove the monotonicity property in a general way and the computational cost for the vertex method is extremely expensive, especially for problems with many interval inputs. The last type of core algorithm for the interval analysis is the global optimization method [28–30]. The advantage of this method is that the calculated response interval is relatively tight and the wealth of tools available for the mathematical optimization can be employed. However, two optimization procedures should be performed simultaneously, which results in prohibitive computational cost. Furthermore, two typical preprocessing procedures, i.e. the subinterval technique [23,24,31] for the interval inputs and surrogate model [32–34] for the expensive numerical simulation, are utilized for the accuracy and efficiency improvement, respectively. However, a significant sacrifice in the efficiency for the former or a potential accuracy reduction for the latter is introduced.

The probabilistic and interval methods are perfectly appropriate for the uncertain problems with random and interval parameters, respectively. However, during the realistic analysis of the structural-acoustic system, two types of uncertain parameters may exist simultaneously if the data available on uncertainties are different. In this context, researches on the acoustic analysis with random and interval parameters and elegant methods in a dual-layer framework have been reported, which can be divided into two categories. In the first type of methods, the statistical characteristics of the system response at any realization of the interval parameters are derived based on the perturbation theory and the interval statistical moments of the response are furtherly calculated using the vertex method [35,36], the first-order Taylor series expansion method [37–39] and MC [36]. However, these methods are effective only for problems with small uncertainties, especially for the nonlinear ones. Besides, either rewriting the program codes or extractions of the dynamic stiffness matrix as well as load vector for the structural-acoustic system is necessary for these intrusive methods. In the other type of methods, surrogate models of the system response w.r.t. the random and interval parameters, e.g. the first-order Taylor series expansion [40], hybrid surrogate model of PCE and response surface [41], and Gegenbauer series expansion [42], are firstly established and MC is adopted to calculate the intervals of the statistical characteristics. However, the computational cost of MC will increase dramatically [36] and the accuracy may be unacceptable, e.g. an interval translation effect induced by the first-order Taylor series expansion.

To overcome potential limitations for current methods, the focus of this paper is to develop a non-intrusive method for the hybrid uncertainty propagation in structural-acoustic systems. Thus, a dual-layer procedure named the