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Fuzzy interval Finite Element/Statistical Energy Analysis for mid-frequency analysis of built-up systems with mixed fuzzy and interval parameters

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ABSTRACT

This paper introduces mixed fuzzy and interval parametric uncertainties into the FE components of the hybrid Finite Element/Statistical Energy Analysis (FE/SEA) model for mid-frequency analysis of built-up systems, thus an uncertain ensemble combining non-parametric with mixed fuzzy and interval parametric uncertainties comes into being. A fuzzy interval Finite Element/Statistical Energy Analysis (FIFE/SEA) framework is proposed to obtain the uncertain responses of built-up systems, which are described as intervals with fuzzy bounds, termed as fuzzy-bounded intervals (FBIs) in this paper. Based on the level-cut technique, a first-order fuzzy interval perturbation FE/SEA (FFIPFE/SEA) and a second-order fuzzy interval perturbation FE/SEA method (SFIPFE/SEA) are developed to handle the mixed parametric uncertainties efficiently. FFIPFE/SEA approximates the response functions by the first-order Taylor series, while SFIPFE/SEA improves the accuracy by considering the second-order items of Taylor series, in which all the mixed second-order items are neglected. To further improve the accuracy, a Chebyshev fuzzy interval method (CFIM) is proposed, in which the Chebyshev polynomials is used to approximate the response functions. The FBIs are eventually reconstructed by assembling the extrema solutions at all cut levels. Numerical results on two built-up systems verify the effectiveness of the proposed methods.

1. Introduction

In engineering design, the vibro-acoustic analysis of complex systems is an important issue that should be carefully taken into consideration. Before performing the vibro-acoustic analysis, selecting a suitable approach to model the corresponding system is necessary. The Finite Element Method (FEM) [1] is a widely used technique for low frequency vibro-acoustic analysis, but for mid-high frequency vibro-acoustic analysis, it requires a large number of degrees of freedom, and thus leads to a heavy computational burden. The Statistical Energy Analysis (SEA) [2] is a specifically developed method for high frequency vibro-acoustic analysis, in which the system is excited by sufficiently high frequency excitation and assumed to be highly random. Compared with FEM, SEA requires much fewer degrees of freedom and achieves a much higher computational efficiency. For mid-frequency vibro-acoustic analysis, which is the target problem of this paper, neither FEM nor SEA

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is suitable, and a hybrid method combining FEM and SEA is applicable, termed as the hybrid FE/SEA method [3]. In FE/SEA, a complex built-up system is usually divided into two parts: the FE components (master system) modeled using FEM and the SEA subsystems modeled using SEA. The SEA subsystems are assumed to possess high randomness, which is modeled as non-parametric uncertainty; while the FE components are assumed to be fully deterministic. Lots of research works related to FE–SEA have been done by Langley and co-workers [4–7].

However, in engineering practice, parametric uncertainties caused by varieties of factors, such as the manufacturing tolerances or unpredictable external excitations, are inevitable, thus it is reasonable to consider the FE components of the hybrid FE/SEA model as uncertain rather than deterministic. Generally, parametric uncertainties can be classified into two different types: probabilistic and non-probabilistic uncertainties. Probabilistic method [8,9] is the prior way to describe the parametric uncertainties when the probability distribution functions of uncertain parameters can be defined unambiguously. Under the circumstance that the statistical information is insufficient to construct the probability distribution functions of uncertain parameters, the non-probabilistic method [10,11] comes into use. For instance, the non-probabilistic interval method [12,13] is a popular way to describe uncertain parameters whose probability distribution functions are unavailable but bounds are well defined. For the interval analysis, many approaches have been proposed. The interval perturbation finite element method (IPFEM) [14] is a highly efficient and widely used technique, but an obvious drawback is that its application is limited to the interval analysis with small uncertainties. Recently, a Chebyshev interval method [15] and a Legendre orthogonal polynomial based method [16] were proposed for solving interval ordinary differential equation systems and handling interval uncertainties in SEA for structural–acoustic systems respectively, and the two methods can handling large interval uncertainties. Both the probabilistic and non-probabilistic interval uncertainties have been introduced into the FE components of the hybrid FE/SEA model, thus an uncertain ensemble involving mixed parametric and non-parametric uncertainties comes into being [17,18]; Monte Carlo Simulation (MCS) [19,20] of the hybrid FE/SEA model was employed to deal with the parametric uncertainties, which could lead to an extremely low efficiency, especially in the uncertain analysis of large scale built-up systems. Two different asymptotic statistical techniques are proposed to handle the probabilistic uncertainties in the FE components of the hybrid FE/SEA model: namely the First Order Reliability Method and Laplace's method [21], which can handle probabilistic uncertainties efficiently with good accuracy. Based on the Taylor series and subinterval technique [22], a second-order interval perturbation Finite Element/ Statistical Energy Analysis (SIPFE/SEA) and the subinterval technique based on SIPFE/SEA are proposed to hand non-probabilistic interval uncertainties in the structure–acoustic systems modeled by FE/SEA [23]. Up to now, researches of introducing parametric uncertainties into the hybrid FE–SEA framework for uncertain mid-frequency analysis are mainly concentrated on probabilistic and interval model, other types of parametric uncertain model are still unexplored.

The fuzzy set theory, which was introduced by Zadeh [24] in 1965, is another category to describe the parametric uncertainties with limited objective information in a non-probabilistic way. Different from the probabilistic theory using the probability distribution function constructed from sufficient objective information, the fuzzy set theory uses the member function, which is obtained from expert subjective opinions, to describe the uncertain parameters. The fuzzy set theory has been applied in a variety of fields. In the engineering field, the fuzzy finite element method (FFEM) is a popular method for uncertain system analysis with fuzzy uncertainty, such as the static analysis, natural frequency analysis and dynamic analysis of uncertain structures [25–27], heat conduction problems with uncertain parameters [28]. By using the level-cut technique [26], FFEM can be decomposed into a series of interval finite element methods (IFEMs). Based on this idea, efficient interval analysis methods can be extended to implement the fuzzy analysis, such as the global optimization based approach [29], the classical interval arithmetic [30] and the perturbation method [31]. Recently, the fuzzy set theory was merged into the SEA method for energy flow prediction between structural vibrating systems coupled by joints with fuzzy uncertainties [32], and a method based on Legendre polynomial approximation was proposed to handle the fuzzy uncertainties. In comparison with other fuzzy analysis methods, the fuzzy perturbation method is quite simple and requires much less computational cost.

In recent years, uncertain analysis with mixed parametric uncertainties has got more and more attention, which is mainly due to the fact that different types of parametric uncertainties may exist simultaneously in practical engineering problems. Gao et al. [33] developed a random interval perturbation method for uncertain structure analysis with hybrid random and interval parameters; Xia et al. [34] proposed a hybrid perturbation vertex method for uncertain structure–acoustic analysis with hybrid random and interval parameters; Chen et al. [35] proposed a hybrid perturbation method for uncertain exterior acoustic field analysis with random and interval parameters; Wu et al. [36] proposed a Polynomial-Chaos-Chebyshev-Interval method to handle the hybrid random and interval uncertainties in vehicle dynamics; Cicirello and Langley [18] employed the MCS of the hybrid FE/SEA method to deal with mixed random and interval uncertainties in built-up structures. For hybrid uncertain problems with fuzzy and random parameters, Sniady et al. [37] presented a spectral approach for fuzzy stochastic analysis of uncertain structures; Wang et al. [38] proposed a fuzzy stochastic perturbation method for uncertain temperature field prediction; Chakraborty and Sam [39] proposed a equivalent transformation method for structure reliability analysis by transforming fuzzy variables to equivalent random variables; Li and Lu [40] proposed an interval optimization based line sampling method for hybrid fuzzy and random reliability analysis. All the above hybrid uncertain analysis methods involve probabilistic uncertainties. However, at the early stage of engineering design, it is difficult to collect sufficient information to construct a probabilistic model, thus developing effective hybrid non-probabilistic uncertain analysis methods is meaningful. Nie et al. [41] presented a hybrid interval-parameter fuzzy robust programming approach for waste management planning under fuzzy and interval uncertainties; Wang et al. [42] proposed a