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Unified analysis approach for the energy flow in coupled vibrating systems with two types of hybrid uncertain parameters

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ABSTRACT

For determining the energy flow in coupled vibrating systems with limited information, two hybrid uncertain models have been introduced to model the uncertain parameters. One is the hybrid probability and interval model in which the probability and interval variables exist simultaneously. The other one is the hybrid interval probability model in which some distribution parameters of the probability variables are given as interval variables. A hybrid stochastic interval perturbation method (HSIPM) is proposed for the unified energy flow analysis in coupled vibrating systems under two hybrid uncertain models. In the proposed method, by temporarily neglecting the uncertainties of interval variables, the first-order stochastic perturbation method is adopted to calculate the expectation and variance of the energy vector. Afterwards, the interval of the expectation and variance of the energy vector can be obtained by the first-order interval perturbation method. Two numerical examples are given to illustrate the feasibility and effectiveness of the proposed method.

1. Introduction

The study of the coupling of multimodal systems is an interesting topic for both the low-medium frequency and the high-frequency problems. Finite element models are often employed to capture the detailed deformation of coupled multimodal systems in low frequency regions. The hybrid deterministic-statistic modeling techniques are usually used to predict the coupled multimodal systems in the medium frequency [1–3]. In high-frequency regions, energy-based methods are usually used to describe the vibrational behavior of mechanical systems. For instance, the statistical energy analysis (SEA) is implemented in high-frequency when studying the response of structures or acoustic cavities excited by broad band forces. To find the response of a complex structure (a set of subsystems coupled together), the SEA method utilizes a set of equations, not necessarily differential, to describe the interaction between the subsystems rather than the dynamic balance between infinitesimal volumes. In the SEA method, the energy balance of the constituent subsystems is investigated through mathematical manipulations and the joints are considered as independent subsystems. A potential alternative to SEA is the power flow approach, whose advantage lies in the possibility of modeling the spatial distribution of energy

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density at high frequencies. Thus, the power flow approach can yield a more effective estimate of the system behaviors than the average response given by SEA. Therefore, the investigation of the energy flows between mechanical systems is quite important. However, all measured mechanical parameters of the subsystems contain some level of uncertainty in real engineering and these uncertainties may cause significant variability in system performance. So these uncertainties need to be properly taken into account.

In the past decades, there has been an increasing focus in studying predictive methods for the response of systems with uncertain parameters. The traditional analysis techniques are generally on the basis of the probabilistic model, in which the probability distributions of uncertain parameters are unambiguously defined based on the available information. The Monte Carlo method (MCM) is still the most versatile probabilistic method for probabilistic problems so far [4–7]. However, due to its excessive computational cost, the MCM is not applicable to the large-scale probabilistic engineering problems. Except for the MCM, many other analysis techniques for probability problems have been well established, and have acquired significant successes, which include the perturbation stochastic finite element method [8–11], the spectral stochastic finite element method [12–17], the Bayesian approach [19–22], the model falsification method [18] and so on. By using the probabilistic approaches, a great amount of statistical information or experimental data is required to construct the precise probability distributions of uncertain parameters. Unfortunately, in many practical applications, the information to establish the precise probability distributions of uncertain parameters is not always available or limited. Thus, some suitable assumptions for the probability distributions of random variables have to be made. However, these assumed probability distributions may be unreliable and the analysis results obtained by the probabilistic approach based on these assumed probability distributions may be incorrect [23].

To overcome the above deficiency of probability approach, the interval analysis can be employed. Moffat [24] has illustrated the use of interval uncertain analysis in planning experiment, which is considered as a practical guideline for engineering applications. McWilliam [25] has investigated the least favorable displacement of structures with uncertain (but-non-random) parameters. On the basis of interval analysis, Qiu and Wang [26] have proposed a parameter perturbation method for dynamic response of structures with uncertain-but-bounded parameters. The main defect of the interval analysis is that only the response bounds can be obtained. The response probability distributions in variation ranges are missing.

To keep the advantages of the probability approach and the interval analysis simultaneously, two hybrid uncertain models have been developed. The first one is the hybrid random and interval model, in which the random variables are used to treat the uncertain parameters with sufficient information to determine the corresponding probability distributions, while the interval variables are used to treat the uncertain parameters with limited information. Significant success has been achieved in the hybrid random and interval model. The stochastic interval responses of the structures with interval parameters under random excitation have been investigated by Muscolino et al. [27–29]. The reliability of the uncertain structures with random and interval variables was investigated by Wang and Qiu [30]. A random interval perturbation method was proposed by Gao et al. [31,32] for the response analysis of the uncertain structures with both random and interval parameters. Based on the work of Gao et al. the hybrid perturbation vertex method for the uncertain structure-acoustic problem with both random and interval variables was proposed by Xia and Yu [33,40]. Recently, a hybrid perturbation method for the prediction of the exterior acoustic field with interval and random variables has been developed by Chen et al. [34].

The second type of the hybrid uncertain model is the interval random model, in which all the uncertain parameters are quantified by the probability model, whereas some of their distribution parameters with limited information can only be given as intervals instead of precise values. Researches on the interval random model have also achieved some significance progress. On the basis of the classical probabilistic reliability theory and the interval analysis technique, the failure probabilistic interval of the structures with interval random variables was evaluated by Qiu et al. [35]. By combining the simulation process into the interval analysis, Zhang et al. [36,37] and Hurtado [38] have investigated the interval failure probabilities of the structures with interval random variables. Recently, Xia et al. [39] have proposed an interval random perturbation method to compute the bounds of the expectations and variances of response of the acoustic fields and the structural-acoustic systems with interval random variables.

Though researches on these two hybrid uncertain models mentioned above have achieved significant developments, some important issues like the unified numerical method for the response analysis of these two hybrid uncertain models remain to be solved. Recently, based on the change-of-variable technique and the interval perturbation technique, a unified response probability distribution analysis method for two hybrid uncertain acoustic fields was proposed by Xia et al. [41] to estimate the variation ranges of the response probability distributions of acoustic fields. From the overall perspective, the research on the unified numerical method for the analysis of these two hybrid uncertain models is in its preliminary stage and yet mostly unexplored.

Up to now, many studies have been devoted to the energy flows between mechanical systems with uncertainties. Whereas, the main approaches to treat these uncertainties in mechanical systems are the probability method and the interval method. Radcliffe and Huang [42] presented an algorithm to predict the response variances of automotive vehicles by introducing a stochastic perturbation in SEA equations and the first order approximation technique. Bussow and Petersson [43] developed an analytical approach for the uncertain analysis of systems by introducing a factor indicating the sensitivity of the energy in the subsystem of interest. Gabriele and Culla [44] use the interval mathematics and the random perturbation procedure to compute the energy flow of two coupled subsystems with the uncertain joint directly, and the