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Dynamic response analysis of structure under time-variant interval process model

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A B S T R A C T

Due to the aggressiveness of the environmental factor, the variation of the dynamic load, the degeneration of the material property and the wear of the machine surface, parameters related with the structure are distinctly time-variant. Typical model for time-variant uncertainties is the random process model which is constructed on the basis of a large number of samples. In this work, we propose a time-variant interval process model which can be effectively used to deal with time-variant uncertainties with limit information. And then two methods are presented for the dynamic response analysis of the structure under the time-variant interval process model. The first one is the direct Monte Carlo method (DMCM) whose computational burden is relative high. The second one is the Monte Carlo method based on the Chebyshev polynomial expansion (MCM-CPE) whose computational efficiency is high. In MCM-CPE, the dynamic response of the structure is approximated by the Chebyshev polynomials which can be efficiently calculated, and then the variational range of the dynamic response is estimated according to the samples yielded by the Monte Carlo method. To solve the dependency phenomenon of the interval operation, the affine arithmetic is integrated into the Chebyshev polynomial expansion. The computational effectiveness and efficiency of MCM-CPE is verified by two numerical examples, including a spring-mass-damper system and a shell structure.

1. Introduction

Uncertainties, related with material characteristics, geometric properties, external loads, boundary conditions and environmental factors, unavoidably exist in engineering structures. Dynamic response of the structure seriously suffers from the effects of these uncertainties. Generally, uncertainties are treated as random variables or processes. To represent random variables or processes, a large number of significant works have been done [1]. Shinozuka and Jan [2] characterized the homogeneous random oscillatory process of the multidimensional excitation as an evolutionary power spectrum. Grigoriu [3] evaluated the effectiveness of Karhunen–Loève, spectral and sampling representations for the Gaussian and non-Gaussian stochastic processes. Melink and Korelc [4] investigated the stability of Karhunen–Loève expansion to simulate the Gaussian stochastic fields. Cho et al. [5] developed the Karhunen–Loéve expansion for multi-correlated stochastic processes. Kim and Shields [6] introduced Karhunen–Loève expansion and the iterative translation approximation method to model strongly non-Gaussian, non-stationary stochastic processes. Field and Grigoriu [7] investigated the accuracy of the

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polynomial chaos approximation for the non-Gaussian random variables and stochastic processes. Chen et al. [8] developed a local polynomial chaos expansion to represent the high dimension stochastic inputs. Lu et al. [9] discussed the limitation of the polynomial chaos expansion in the inverse problems. Recently, Mao et al. [10] proposed a new method based on the Hilbert spectrum to represent the non-stationary stochastic processes.

Based on the suitable representations of random variables or processes, plenty of impressive approaches have been developed for the dynamic response problems with deterministic and uncertain system parameters. Monte Carlo method is the simplest and the most versatile method for the dynamic response analysis of stochastic structures [11,12]. The main shortcoming of the Monte Carlo method is its considerable computational burden, especially for the large scale engineering problems. To effectively and efficiently investigate stochastic structures, Culla and Carcaterra [13] proposed two stochastic perturbation methods, named as the conventional perturbation-statistical perturbation method and the statistical linearization-statistical perturbation method, to predict the statistical moments of a moored floating body oscillating in the stochastic waves. Kamiński and Corigliano [14] developed a stochastic perturbation technique for the sensitivity, probabilistic and stochastic analysis of the thermo-piezoelectric phenomena of solid continua. Muscolino et al. [15] presented a semi-analytical approach based on the stochastic perturbation technique and the rational series expansion [16] for the sensitivity analysis of the dynamic response of discretized structures under the Gaussian stochastic excitations. Gao et al. [17] presented a random factor method for the random vibration analysis of stochastic truss structures. Wu and Zhong [18] proposed a hybrid approach, based on the modal analysis, the second-order perturbation technique and the number theoretical method, for the dynamic response analysis of stochastic structures. Adhikari [19,20] introduced the spectral stochastic finite element method for the dynamic response analysis of linear stochastic structures. Soize [21,22] presented a stochastic reduced order model for the dynamical response analysis of structures with stochastic uncertainties.

When the statistical characteristics of uncertain parameters are unambiguously defined, these stochastic representation and operation approaches can be perfectly applied in the dynamic response analysis of uncertain structures. However, information to determine statistical characteristics of uncertain parameters is not always sufficient. In this case, non-probabilistic models [23] are alternative options. Among various non-probabilistic models, the interval model is an important one due to its flexible ability to treat uncertain parameters with limit information. In the interval model, only the variational ranges but not the detailed statistical characteristics of uncertain parameters need to be well-defined. Recently, the interval model and the corresponding interval approaches have been widely applied in the dynamic response analysis of uncertain structures. Chen and Wu [24] proposed an interval optimization method based on the perturbation theory for the dynamic response analysis of the structure with interval parameters. Gao [25] developed an interval factor method for the interval natural frequency and mode shape analysis of truss structures with interval parameters. Qiu et al. [26–28] proposed an interval perturbation method to evaluate the supremum and infimum of the dynamic response of the structure with interval parameters and interval initial conditions. Xia et al. [29–32] developed a modified interval perturbation method based on the modified Neumann expansion for the response analysis of interval structures and interval structural-acoustic systems. Liu et al. [33] presented a new heuristic optimization method to evaluate the minimal and maximal values of the dynamic response of a vehicle-bridge interaction system with interval uncertainties. Ma et al. [34] proposed an interval numerical method combined of the perturbation theory, the interval mathematics and the modal superposition method for the dynamic response analysis of rotors with interval parameters. Wu et al. [35,36] introduced a Chebyshev interval method to estimate the variational ranges of the dynamic responses of interval nonlinear systems and interval multibody mechanical systems. Liu et al. [37] presented a non-intrusive trigonometric polynomial method for the dynamic response analysis of nonlinear systems with interval parameters and interval initial conditions. Muhanna et al. [38–40] proposed a wonderful interval finite-element formulation based on the element-by-element technique and the Lagrange multiplier compatibility constraints to yield the sharp guaranteed solutions for interval linear or nonlinear structures. Muscolino et al. [41,42] developed an excellent interval approach based on the so-called affine arithmetic to limit the catastrophic effects of the dependency phenomenon.

The above remarkable interval methods are based on the interval model in which uncertain parameters are assumed as time-independent. Namely, the variational ranges of interval variables are time invariant in the interested time period. In engineering practices, due to effects of the varying environmental factor, the dynamic exterior excitation, the material property degeneration and the machine surface wear, parameters of structures distinctly possess time-variant characteristics. For example, the thickness of brake blocks, the road excitation, the wind load, the material properties of machine in service, et al. always vary over time. Thus, it is desired to develop an interval process model for the description of the time-variant characteristics of uncertainties. Jiang et al. [43] proposed a non-probabilistic convex process model and applied it in the time-variant dynamic reliability analysis of the structure with limit information. Wang et al. [44] presented a non-probabilistic interval process model and introduced it for the safety evaluation of time-dependent structures. To the best knowledge of author, the research on the non-probabilistic interval process is limited in the time-variant reliability analysis of uncertain structures based on the classical first-passage theory. However, the theoretical foundation and the engineering application of the non-probabilistic interval process in the dynamical response analysis of the structure with time-variant uncertainties are still gaps which need to be filled.

In this work, we investigate the dynamic response of the structure with time-variant uncertainties when information is insufficient. A time-variant interval process model is firstly introduced to qualify the time-dependent uncertainties of the dynamic structures with limited sample data. In the time-variant interval process model, the lower and upper bounds of uncertain parameters are not constants but functions of time. The Monte Carlo method is an optional approach for the