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Research paper

Dynamics of flexible multibody systems with hybrid uncertain parameters

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A B S T R A C T

The most popular way to study the dynamics of a multibody system with random parameters is the probabilistic method under the assumption that the mean values and variances of the random parameters are deterministic. For many engineering systems, however, the mean values and variances of those random parameters are inherently interval parameters. In this work, a new computation method is proposed to study the dynamics of flexible multibody systems with hybrid uncertain parameters, i.e., the random parameters with interval mean values and interval variances. The flexible multibody system of concern is described by using the Absolute Nodal Coordinate Formulation first. Then, the perturbation-based method is developed in order to incorporate hybrid uncertain parameters in the dynamic analysis of flexible multibody systems. Afterwards, the dynamics equations are expanded about the mean values of the uncertain input variables by means of the second-order Taylor series. The Chebyshev collocation method, together with the scanning method, is utilized to generate the interval bounds for the deduced surrogate model. Finally, the interval mean values and interval variances of the system dynamics are obtained by using the interval arithmetic. As a consequence, the proposed method can be degenerated into the pure interval method.

1. Introduction

The past decades have witnessed numerous studies on the dynamics of flexible multibody systems [1–3]. Most of those studies, however, have focused on the dynamics of multibody systems with deterministic parameters. In practice, the multibody systems inevitably contain uncertain parameters, such as the uncertain material properties, uncertain geometrical parameters, and uncertain loading parameters. Therefore, the dynamic analysis of multibody systems without these uncertain parameters taken into account cannot predict their true dynamic behaviors, but only a few studies have dealt with the dynamics of flexible multibody systems with uncertain parameters.

Among the studies on the dynamics of the multibody systems with uncertain parameters, there are two major types of methods to describe the uncertain parameters. One is the probabilistic methods [4] and the other is the non-probabilistic methods [5]. The probabilistic methods are usually used to describe the random parameters with known probability density functions, whereas the non-probabilistic methods are mainly used to solve the uncertain problems without deterministic probabilistic distributions.

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The probabilistic methods can be further classified into two subtypes. The first is the statistical methods, such as the Monte Carlo simulation [6], the reliability-based methods [7] and the response surface methods (RSMs) [8]. The second is the non-statistical methods [4]. Compared with the statistical methods, the non-statistic methods are more efficient and have a broader scope of application, including the differential analysis methods [4] and the polynomial chaos (PC) methods [9,10]. Furthermore, Sandu et al. [11,12] used the PC methods to simulate a rigid planar single pendulum mathematically described by a set of differential-algebraic equations (DAEs). The PC methods employ a series expansions, such as the Karhunen–Loeve expansion, to represent the stochastic processes [13]. The differential analysis methods [4] are more efficient than other probabilistic methods. The differential analysis methods [4] can be further classified as the Neumann expansion method [14] and the perturbation method [15]. The Neumann expansion method [14] involves finding the inverse of the model operator through the expansion of the model equations, which will cause a limitation to the type of model equations. The perturbation method [15] involves the expansion of model outputs as a series of small random perturbations in system parameters, and the subsequent solution of the series coefficients. For the differential analysis methods, nevertheless, the conditions of small perturbation should be satisfied. For all these probabilistic methods, a great amount of statistical information is required to construct the precise probability distribution functions of uncertain parameters. However, it is well known that it is very difficult to obtain the complete deterministic probabilistic information of random parameters in engineering.

The interval parameters are defined as uncertain, but bounded parameters. The interval methods are a type of non-probabilistic methods and mainly used to study the problems with uncertain, but bounded parameters. It is usually easier to get the bounds of the interval parameters than to obtain the probability density functions of random parameters. The interval arithmetic is one of the most computationally efficient ways to evaluate the bounds of an interval polynomial function (also called the surrogate model) [16]. Viegas et al. [17] performed the kinematic analysis of the parallel kinematic machines by taking into account the uncertainty of the involved parameters via interval arithmetic. Some other researchers used the interval methods, such as the Taylor series method [16,18], the Taylor model method [19,20], and the hybrid method [21], to solve simple perfect dynamics problems [18–22]. Recently, based on the Chebyshev interval algorithm presented by Wu et al. [5,23–25], Wang et al. [26] further used a Chebyshev tensor product (CTP) sampling method and a Chebyshev collocation method (CCM) to study the flexible multibody systems with interval parameters. In the work by Wang et al. [26], they used the Absolute Nodal Coordinate Formulation (ANCF) [3] to accurately model the flexible multibody systems subject to both large overall motions and large deformations [27]. Furthermore, they determined the lower and upper bounds of the dynamic responses by scanning the Chebyshev surrogate model, instead of scanning the Interval Differential Algebraic Equations (IDAEs) so as to improve the computational efficiency significantly. In their work [26] they also initially studied the dynamics of a complex uncertain rigid-flexible multibody system, that is, a six-arm space robot with six interval parameters. Furthermore, they also performed the dynamic analysis of a flexible multibody system with uncertain joint clearance [28] and the sensitivity analysis of flexible multibody systems with interval parameters [29].

In engineering, many systems simultaneously involve probabilistic and interval uncertainties, such as the uncertain probabilistic load and the interval design parameters. Zaman et al. [30] proposed a probabilistic framework to represent uncertainties from interval non-probabilistic data. Du et al. [31] developed a computational method involving a nested probabilistic analysis and interval analysis. Chen et al. [32] presented a hybrid perturbation method for the prediction of exterior acoustic field with interval and random variables. Wang et al. [33] proposed a hybrid uncertain finite element method for the uncertain temperature field prediction involving random, fuzzy and interval parameters simultaneously in material properties, external loads and boundary conditions. Wu et al. [34] proposed a Polynomial-Chaos-Chebyshev-Interval method to solve the dynamics of a roll plan model of four degree of freedom and with hybrid uncertainties.

Most previous studies, however, dealt with the systems with random parameters with deterministic mean values and variances or with only interval parameters. Few studies have focused on the hybrid uncertain parameters, that is, the random parameters with interval mean values and interval variances. In fact, Quaranta [35] pointed out that “the mean value is approximately equal to…” and “the variance lies in the range …”. Qiu et al. [36] also demonstrated the importance of considering “imprecise probability” in engineering applications. Therefore, the system with the hybrid uncertain parameters taken into account can give more dynamic information than that with only one type of uncertain parameters. In the work by Qiu et al. [36], they studied the simple truss structures with uncertain loads, and meanwhile considered the reliability index and the failure probability as interval parameters. Zhang et al. [37] proposed a probability box method to model the imprecise probability distribution, and gave an interval quasi-Monte Carlo simulation method to evaluate interval bounds of structure failure probabilities. However, the interval quasi-Monte Carlo simulation method can only handle simple planar problems due to its low efficiency. Quaranta [35] performed the finite element analysis of a truss dome with uncertain material properties using the fuzzy probabilities.

To the best knowledge of the authors, no studies have been reported so far on the dynamics of complex spatial flexible multibody systems with hybrid uncertain parameters. Hence, it is necessary to develop to a new computation method to study the dynamics of spatial flexible multibody systems with hybrid uncertain parameters. This work is a continuation of the authors’ previous study [26], and the rest of the paper is organized as follows. In Section 2, the dynamic equations with deterministic probabilities are deduced under the framework of ANCF. In Section 3, the dynamic equations with hybrid uncertain parameters are developed. The Chebyshev collocation method (CCM) is briefly reviewed and used to solve the dynamic equations of the system with interval parameters. The CCM is used to generate the surrogate model for the system.