Dynamic Analysis for Flexible Multibody Systems with Hybrid Uncertainties

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EXTENDED ABSTRACT

1 Introduction

The multibody system has been widely applied in different fields such as the machine, automotive, robot, aerospace system, and many other industries. To accurately simulate flexible multibody systems with large global motion and large deformation, Shabana [1] has proposed the absolute nodal coordinate formulation (ANCF). To compute the dynamical response of a multibody system more accurately, it is demanded to take account the uncertain factors in practical problems [2]. The material properties of the flexible component vary continuously in the space domain. It can be characterized through employing the random field, because the random field can be used to handle randomness and spatial variability simultaneously. The Karhunen-Loeve (K-L) expansion is an effective series expansion method which aims at discretizing the random field to countable random variables [3].

Feng et al. [4] have proposed the polynomial-chaos-Legendre-metamodel (PCLM) for the case that the dynamical system contains both random and interval parameters. In order to improve the accuracy and efficiency of PCLM, the selection of sample points is very important. Compared with the traditional probabilistic collocation method (PCM), coherence optimal sampling in this study makes the results of least square method more stability and accurate. Therefore, an improved method has been proposed by combining the PCLM and coherence optimal sampling, and it has been applied to flexible multibody systems.

2 Problem description: Multibody system with hybrid uncertainties

In this paper, the absolute node coordinates (ANCF) is used to describe the deformation of flexible body. The dynamic equations for multibody systems with hybrid uncertainties based on the ANCF can be expressed by

$$\begin{cases} \tilde{\mathbf{M}}\left(\boldsymbol{\xi},[\boldsymbol{\eta}]\right)\ddot{\mathbf{q}}+\tilde{\mathbf{F}}\left(\mathbf{q}\left(\boldsymbol{\xi},[\boldsymbol{\eta}]\right)\right)+\tilde{\boldsymbol{\Phi}}_{\mathbf{q}}^{\mathrm{T}}\left(\mathbf{q}\left(\boldsymbol{\xi},[\boldsymbol{\eta}]\right),t\right)\boldsymbol{\lambda}\left(\boldsymbol{\xi},[\boldsymbol{\eta}]\right)=\tilde{\mathbf{Q}}\left(\mathbf{q}\left(\boldsymbol{\xi},[\boldsymbol{\eta}]\right),\dot{\mathbf{q}}\left(\boldsymbol{\xi},[\boldsymbol{\eta}]\right)\right) \\ \tilde{\boldsymbol{\Phi}}\left(\mathbf{q}\left(\boldsymbol{\xi},[\boldsymbol{\eta}]\right),t\right)=\mathbf{0} \end{cases}. \tag{1}$$

where $\boldsymbol{\xi}=\left[\xi_1\ \xi_2 \cdots \xi_n\right]$ and $[\boldsymbol{\eta}]=\left[[\eta_1][\eta_2]\cdots[\eta_m]\right]$ denote n-dimensional random uncertain parameter and m-dimensional interval uncertain parameter, respectively.

3 The hybrid uncertain analysis method

The implementation process of hybrid uncertain analysis method PCIM mainly contains five steps:

(1) Describe the material properties of flexible components as the random field $\hat{H}(\mathbf{x},\theta)$ and expand continuous random fields to a Fourier-type series by the K-L expansion method, that is

$$H(\mathbf{x},\theta)=\mu(\mathbf{x})+\sigma(\mathbf{x})\sum_{i=1}^{m}\sqrt{\lambda_i}\,\xi_i(\theta)\,f_i(\mathbf{x})\ . \tag{2}$$

(2) Construct the surrogate model of dynamic response by using PCLM, which contains both the random variables $\boldsymbol{\xi}$ and interval variables $[\boldsymbol{\eta}]$. The polynomial chaos (PC) method and the Legendre metamodel (LM) method are respectively applied to obtain the measurement matrix $\boldsymbol{\Psi}(\boldsymbol{\xi})$ and $\boldsymbol{\Phi}(\boldsymbol{\eta})$ corresponding to random variables and interval variables.

(3) Produce the sampling points by using the traditional probabilistic collocation method and the coherence optimal sampling.

(4) Build the dynamic equations of multibody systems by using the ANCF method. For a set of fixed $\boldsymbol{\xi}$ and $[\boldsymbol{\eta}]$, Eq. (1) is reduced to deterministic differential algebraic equations, and the generalized-α method is used to produce a numerical solution $\mathbf{F}(\boldsymbol{\xi},\boldsymbol{\eta})$.

(5) Calculate the coefficients matrix $\boldsymbol{\beta}$ by the following formulation

$$\boldsymbol{\beta}=\left(\boldsymbol{\Phi}(\boldsymbol{\eta})^{\mathrm{T}}\boldsymbol{\Phi}(\boldsymbol{\eta})\right)^{-1}\boldsymbol{\Phi}(\boldsymbol{\eta})^{\mathrm{T}}\mathbf{F}(\boldsymbol{\xi},\boldsymbol{\eta})^{\mathrm{T}}\boldsymbol{\Psi}(\boldsymbol{\xi})\left(\boldsymbol{\Psi}(\boldsymbol{\xi})^{\mathrm{T}}\boldsymbol{\Psi}(\boldsymbol{\xi})\right)^{-1}. \tag{3}$$

Finally, calculate evaluation index for hybrid uncertain problems: the interval mean (IM) and the interval error bar (IEB).

4 Case studies

As shown in fig. 1, two numerical examples are employed to test the performance of the proposed method: (a) A flexible double pendulum system subjected to torque; (b) Spacecraft structure with central rigid body and flexible truss. The results of evaluation indexes (IM and IEB) based on the presented method are shown in the fig. 2. And the results of the flexible double pendulum system are compared with the Monte Carlo-Scanning method (MCS). The numerical results show that the maximum relative error of IM is 0.37% and that of IEB is 0.66% compared with MCS method. The error is small and the fitting accuracy is high.

By comparing five sampling methods, the results show that the computational efficiency of coherence optimal sampling is relatively high, followed by monomial cubature rules (MCR) method. When selecting sample points based on the PCM or ECM (efficient collocation method), results obtained by different sample point combinations are not the same, resulting in unstable calculation results. All the sample points determined by coherence optimal sampling method can be used in the calculation process, and the calculation result is more stable. The accuracy of FFNI (full factorial numerical integration) is high, but the number of sample point groups required by FFNI increases exponentially with the increase of PCLM order and variable dimension.

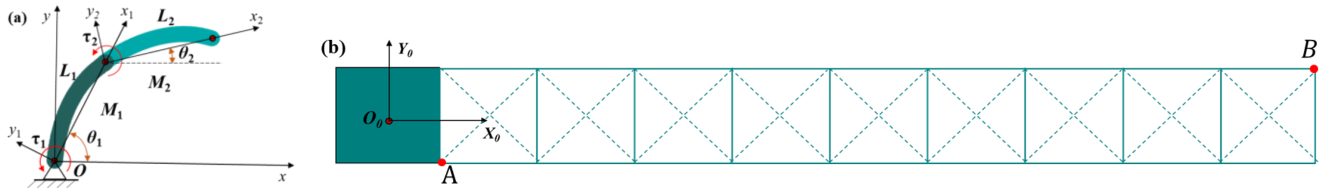

Figure 1: (a) A flexible double pendulum system; (b) Spacecraft structure with central rigid body and flexible truss.

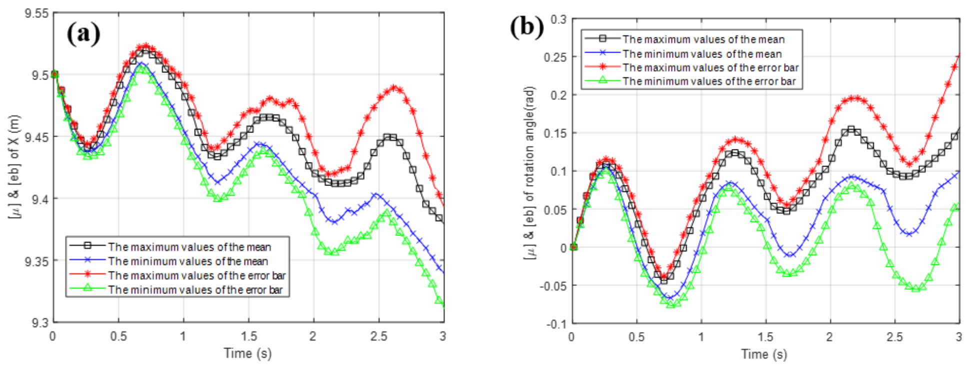

Figure 2: Evaluation indexes of: (a) the displacement response at point B; (b) the angular response at point A.

5 Conclusions

In this paper, a non-intrusive polynomial-chaos-Legendre-metamodel method based on the generalized-α algorithm is proposed for multibody systems involving hybrid uncertainties, namely the random field and interval variables. The component geometry sizes are regarded as interval parameters, while the material properties are described as the random fields, which are discretized to countable random variables by the K-L expansion method. The ANCF modeling method is used to mesh the flexible body, and the generalized-α algorithm is used to solve nonlinear algebraic equations with uncertain parameters. The surrogate model of dynamic response is constructed by using the PCLM method. On this basis, the original algorithm is improved through optimizing the samples. Coherence optimal sampling is used to generate high-quality sample points, which makes the calculation results of the least squares method more accurate. The correctness of the results is verified by comparing both types of evaluation indexes with the Monte Carlo-Scanning method. And compared with traditional sampling methods, the coherence optimal sampling method has higher computational efficiency. The simulation results show that the influence of parameter uncertainties on system response cannot be ignored, and the proposed method is effective and applicable to the study of dynamic characteristics of flexible multibody systems with hybrid uncertain parameters.

References

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