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Reliability analysis of uncertain dynamical systems using correlated function expansion

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ABSTRACT

Reliability analysis of uncertain dynamical systems is considered. The excitations are modeled as non-stationary Gaussian processes, whereas parametric uncertainties due to structural randomness are modeled as non-Gaussian random variables. The structural responses are, therefore, non-Gaussian processes. The limit state is formulated in terms of the extreme value distribution of the response process. Developing these extreme value statistics analytically is not straightforward, which makes failure probability estimations difficult. An alternative procedure is investigated for computing exceedance probabilities. Proposed approach involves generating a full functional operational model, which approximates the original limit surface. Once the approximate form of the original limit state is defined, the failure probability can be obtained by statistical simulation. Thus, the method can be integrated with commercial finite element software, which permits uncertainty analysis of large structures with complexities that include material and geometric nonlinear behavior.

1. Introduction

A vibrating structural/mechanical system with parametric uncertainty is deemed to be safer if its response process lies well below the specified thresholds over a given duration of the load process. Thus, extreme values of responses play a crucial role in the estimation of structural reliability. We refer to a recent review paper [1] and a special issue of a journal [2] for further works on structural dynamics with uncertainty. Stochastic analysis of dynamic systems can be conducted either using the random eigenvalue problem (e.g. [3]) or using the dynamic stiffness approach [4]. In this context, the theory of asymptotic distributions [5,6] can be used to study the extreme values of random processes. As an alternative, extreme value theory of random processes over a given period can be related to the probability distribution of first passage times. For stationary Gaussian processes, above two approaches lead to Gumbel models for the extreme responses, provided the joint probability density function (PDF) of the process and its derivative at a given instant are known. It can also be noted that, determination of the joint PDF for Gaussian random responses is straightforward, while for non-Gaussian process evaluation of joint statistics is extremely difficult task.

Several authors have considered reliability and response moments of linear systems under uncertainty, see for example [7–10]. Few studies on the exceedance probabilities of non-Gaussian random processes are reported in the literature [11–13]. von Mises stress, defined by $V(t)=\sqrt{\sigma(t)\mathbf{C}\sigma(t)}$, $\sigma(t)$ is stress tensor [14], is a commonly studied non-Gaussian process, the exceedance probabilities of which are often required for estimating reliabilities [15] of ductile structure. Analytical expressions for the mean outcrossing rate of von Mises stress are developed [16] for linear structures using outcrossing approximations. Several approaches are also developed [17–19] for computing the root mean square of von Mises stress. However, in real-life problems, where the finite element (FE) method is an essential tool for handling the modeling complexities, it is difficult to apply these methods as the performance function is defined in an implicit form. For this class of problems, surrogate models [14,20] provide a promising alternative solution scheme for estimating the exceedance probability of the response. The method developed in this paper belongs to this class of solution technique.

Recently, the authors developed a new computational framework for stochastic FE analysis and time-invariant reliability analysis [21–23]. In the present study we investigate the scope of the correlated function expansion (CFE) approach, by considering the reliability analysis of nonlinear, randomly parametered dynamical systems, subjected to non-stationary Gaussian excitations. The structure is modeled and analyzed using a commercial FE software (e.g. ANSYS). External software builds the full functional operational model using CFE and is interfaced with the FE

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