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Reliability sensitivity analysis of stochastic finite element models

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Abstract

This contribution presents a scheme for integrating a model reduction technique into a simulation-based method for reliability sensitivity analysis of a class of medium/large nonlinear finite element models under stochastic excitation. The solution of this type of problems requires a large number of finite element model re-analyses to be performed over the space of system parameters. A component mode synthesis technique is implemented to carry out the sensitivity analysis in a reduced space of generalized coordinates. The reliability sensitivity analysis is performed by an approach based on a simple post-processing of an advanced sampling-based reliability analysis. The feasibility and effectiveness of the proposed scheme is demonstrated on a bridge finite element model under stochastic ground excitation.
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1. Introduction

One of the objectives of reliability sensitivity analysis is to study the influence of probabilistic model parameters onto the reliability of a given structural system [1–4]. In this context, the system parameters involved in the sensitivity analysis are modeled by a random vector whose joint probability distribution is explicitly known and dependent on a certain number of parameters. For example if the system parameters are modeled as normal or lognormal, the distribution parameters may represent the mean value, standard deviation and correlation coefficients of the system parameters. This situation corresponds to the common case where the mean value corresponds to the ideal value of a system parameter and the standard deviation and correlation coefficients model the uncertainty of the parameters, due to for example the inherent variability in the manufacturing and construction processes. The determination of the variation in the reliability, or equivalently in the failure probability, due to changes in the probabilistic model parameters can provide practical and relevant information. For example, it can identify the most influential system parameters and it can give an important insight on system failure that can be used for general risk-based decision making problems [5,4].

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A classical measure of the effect of distribution parameters on the system reliability is calculating the partial derivative of the failure probability with respect to the distribution parameters. This problem has been addressed in a large number of contributions, where standard approaches such as first- and second-order reliability methods have been used [6–8]. These methods are quite general and easy to implement but their range of application is somewhat limited specially for complex and involved structural systems. In this regard, simulation-based methods offer a feasible means to perform reliability sensitivity analysis of more complex systems. In fact, in [9] a method combining Monte Carlo simulation with a linear approximation scheme allows estimating the sought sensitivity. Similarly in [10–12] estimators for the sensitivity based on simulation methods such as importance sampling, subset simulation and line sampling have been proposed, respectively. On the other hand a meta-model-based importance sampling for efficient reliability sensitivity analysis has been recently presented in [1]. A common aspect of the aforementioned approaches is that they are a simple post-processing of a sampling-based reliability analysis. They have been validated and illustrated in a series of reliability problems involving limit state functions defined in terms of explicit functions or system responses corresponding to relatively simple systems. Recently, the authors have extended the use of simulation-based methods for reliability sensitivity analysis of a certain class of nonlinear structural systems under stochastic excitation [13]. Numerical results showed that on average the estimates generated by the proposed approach converge to reference results obtained directly by Monte Carlo simulation. Validation calculations also indicated that the proposed approach is much more efficient than Monte Carlo, specially when estimating reliability sensitivity measures of systems with small failure probabilities.

Within this framework, it is the objective of this contribution to extend the aforementioned sensitivity approach for a reliability sensitivity analysis of a class of medium/large nonlinear finite element models subject to stochastic excitation. This type of problems appear in a number of realistic situations related to, for example, earthquake engineering, offshore engineering, wind engineering, etc. The main difficulty in estimating reliability sensitivity measures for this type of problems is that a large number of finite element model re-analyses are required over the space of system parameters. To cope with this difficulty, a model reduction technique is proposed to carry out the sensitivity analysis in a reduced space of generalized coordinates. In particular, a method known as component mode synthesis is implemented in the present formulation [14–16]. The method involves dividing the structure into a number of components obtaining reduced-order models of the components and then assembling a reduced-order model of the entire structure. More specifically, after the division of the structure into components the model reduction technique involves two basic steps: definition of sets of component modes; and coupling of the component-mode models to form a reduced-order system model. If the division of the structure into components is guided by a certain parametrization scheme in terms of the system parameters, substantial computational savings can be achieved in estimating the reliability sensitivity measures avoiding system reanalyses for different values of the parameters [17,16]. Moreover, the drastic reduction in computational efforts is obtained without compromising the accuracy of the sensitivity estimates.

In brief, the novel aspect of this contribution is the integration of a model reduction technique into a simulation-based method for local reliability sensitivity analysis of a class of medium/large nonlinear finite element models under stochastic excitation. The organization of the paper is as follows. Section 2 presents the mathematical model of the problem of interest. The reliability and sensitivity assessment of dynamical systems under stochastic excitation are reviewed in Sections 3 and 4, respectively. The theoretical background of component mode synthesis and its integration with the reliability sensitivity analysis are discussed in Section 5. The effectiveness of the proposed scheme is demonstrated in Section 6 with the reliability sensitivity analysis of a bridge structural model under stochastic ground excitation. The paper closes with some conclusions and final remarks.

2. Mathematical model

In this work attention is focused to structural dynamical systems satisfying the following set of coupled non-linear differential equations

$$\begin{aligned}&\mathbf{M}\ddot{\mathbf{x}}(t)+\mathbf{C}\dot{\mathbf{x}}(t)+\mathbf{K}\mathbf{x}(t)+\mathbf{k}(\mathbf{x}(t),\dot{\mathbf{x}}(t),\mathbf{y}(t))=\mathbf{f}(t)\\&\dot{\mathbf{y}}(t)=\boldsymbol{\kappa}(\mathbf{x}(t),\dot{\mathbf{x}}(t),\mathbf{y}(t))\end{aligned}\tag{1}$$

where $\mathbf{x}(t)$ denotes the displacement vector of dimension n, $\dot{\mathbf{x}}(t)$ the velocity vector, $\ddot{\mathbf{x}}(t)$ the acceleration vector, $\mathbf{k}(\mathbf{x}(t),\dot{\mathbf{x}}(t),\mathbf{y}(t))$ the vector of non-linear restoring forces, $\mathbf{y}(t)$ the vector of a set of variables which describes the state of the nonlinear components, $\boldsymbol{\kappa}$ represents a non-linear vector function, and $\mathbf{f}(t)$ the external force vector. The

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