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Reliability sensitivity estimation of nonlinear structural systems under stochastic excitation: A simulation-based approach

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Highlights

- Reliability is defined in terms of first excursion probabilities.
- Proposed approach is a simple post-processing of subset simulation.
- Sensitivity analysis is performed for different levels of system reliability.
- Proposed approach is applicable for complex nonlinear systems.
- Sensitivity information gives a valuable insight into the system reliability.

Abstract

This work explores the feasibility of using advanced simulation-based methods for reliability sensitivity analysis of nonlinear structural systems subject to stochastic excitation. Reliability is defined in terms of a first excursion probability which measures the chances that uncertain structural responses exceed in magnitude prescribed threshold levels within a specified time interval. The proposed reliability sensitivity analysis consists of applying a simple post-processing step associated with an advanced sampling-based reliability analysis. It does not require any additional system response evaluations. In addition, the method provides information about the whole trend of the reliability sensitivity estimates in terms of the threshold levels. The approach is validated on two nonlinear structural models under stochastic ground excitation.

Keywords: Sensitivity analysis; Non-linear structural systems; Reliability; Simulation methods; First excursion probability; Post-processing

1. Introduction

Reliability analysis allows the possibility of accounting for the unavoidable effects of uncertainty over the performance of a structure. In this context the level of safety of a structure can be measured in terms of the reliability, which is a metric of plausibility that the structure fulfills certain performance requirements during its lifetime. Thus, reliability can be incorporated as one of the performance criteria in the analysis and design to address explicitly the effects of

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uncertainty [1]. Even though reliability information is essential, it is also important to analyze the sensitivity of the reliability with respect to variations in system parameters [2–4]. In particular, the determination of the variation in the reliability (or equivalently in the failure probability) due to changes in system parameters can provide useful information. For example it can be used to identify the most influential system parameters and it can provide an important insight on system failure for risk-based decision making, such as robust control or reliability-based design optimization [5–8].

The subject of reliability sensitivity has been addressed in a large number of contributions [9–12]. For example sensitivity analysis of reliability estimates using approximate methods such as first- and second-order reliability methods has been thoroughly studied in the literature for problems involving components or system reliability [2,13,4]. These approaches take advantage of the so-called design point and the eventual correlations between different individual failure modes in order to estimate the sought sensitivity efficiently. While these approximate methods are relatively easy to implement their range of application is somewhat limited specially for complex and involved structural systems. In fact, these methods may suffer from incorrect assumptions regarding the level of non-linearity of the limit state surfaces and the uniqueness of the most probable failure point that is difficult to check in practical applications. Reliability sensitivity analysis has also been studied within the framework of simulation-based methods. For instance, an algorithm for estimating the gradient of the failure probability using either Monte Carlo simulation or Importance sampling has been proposed in [14]. An alternative approach based on a conditional sampling technique was introduced in [15] and further developed in [16]. The key issue of these approaches is the association of an instrumental variability with the deterministic design variables involved in the sensitivity analysis. Using a similar idea, an algorithm was developed in [17] which enables the identification of a reduced set of design parameters that minimizes the failure probability. From that information, a sensitivity analysis is proposed and it is applied to the robust control of the dynamic behavior of structural systems. In principle, simulation-based sensitivity analyses can handle more general cases than standard approaches based on, for example, first- and/or second-order reliability methods.

In this contribution it is assumed that the system parameters involved in the sensitivity analysis are modeled by a random vector whose joint probability density function is explicitly known and dependent on a certain number of parameters. Such parameters can represent for example the mean value or standard deviation. This condition corresponds to the frequent situation where the distribution parameters group for example, ideal dimensions or structural properties whereas the randomness in the system parameters models the inherent variability in the manufacturing and construction processes. In the framework of simulation-based methods this problem has been addressed in several contributions. For example in [11] a method combining Monte Carlo simulation with a linear approximation scheme allows estimating the sought sensitivity. In [10,12,14] estimators for the sensitivity based on simulation methods such as line sampling, subset simulation and importance 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 [18]. 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 static problems.

Within this context, it is the objective of this work to explore the possibility of extending the use of simulation-based methods for a reliability sensitivity analysis of an important type of problems, namely a certain class of non-linear structural systems subject to stochastic excitation. For reliability purposes the probability that any response of interest exceeds in magnitude some specified threshold level within a given time duration is used to characterized the level of structural safety. This probability is commonly known as the first excursion probability [19]. For dynamical systems under stochastic excitation the corresponding probability integral involves a large number of random variables (hundreds or thousands). The proposed sensitivity analysis is based on subset simulation which is an efficient method for estimating small failure probabilities of high-dimensional problems [20]. The salient feature of the proposed implementation for reliability sensitivity estimation when compared to previous simulation-based approaches is the capacity of considering more involved structural systems. For example it allows the treatment of non-linear structural dynamical systems under stochastic excitation and problems involving relatively large finite element models.

In summary, novel aspects of this contribution involve three main aspects. First, it applies an approach for reliability sensitivity analysis of non-linear dynamical systems where uncertainty is modeled considered a large number of parameters. Second, it couples the reliability sensitivity analysis with subset simulation. Although such a task has already been carried out for small scale, simple examples, this contribution presents alternative expressions for determining sensitivity which are considerable simpler. Third, results for reliability sensitivity analysis are performed not only for specific threshold values but for a range of them.