Reliability Engineering and System Safety 107 (2012) 90–106

Contents lists available at SciVerse ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Monte Carlo simulation-based sensitivity analysis of the model of a thermal–hydraulic passive system

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ARTICLE INFO

Article history:
Received 12 October 2010
Received in revised form
20 July 2011
Accepted 22 August 2011
Available online 31 August 2011

Keywords:
Nuclear passive system
Functional failure probability
Reliability sensitivity analysis
Subset Simulation
Line Sampling
Sobol indices

ABSTRACT

Thermal–Hydraulic (T–H) passive safety systems are potentially more reliable than active systems, and for this reason are expected to improve the safety of nuclear power plants.

However, uncertainties are present in the operation and modeling of a T–H passive system and the system may find itself unable to accomplish its function. For the analysis of the system functional failures, a mechanistic code is used and the probability of failure is estimated based on a Monte Carlo (MC) sample of code runs which propagate the uncertainties in the model and numerical values of its parameters/variables.

Within this framework, sensitivity analysis aims at determining the contribution of the individual uncertain parameters (i.e., the inputs to the mechanistic code) to (i) the uncertainty in the outputs of the T–H model code and (ii) the probability of functional failure of the passive system. The analysis requires multiple (e.g., many hundreds or thousands) evaluations of the code for different combinations of system inputs: this makes the associated computational effort prohibitive in those practical cases in which the computer code requires several hours to run a single simulation.

To tackle the computational issue, in this work the use of the Subset Simulation (SS) and Line Sampling (LS) methods is investigated. The methods are tested on two case studies: the first one is based on the well-known Ishigami function [1]; the second one involves the natural convection cooling in a Gas-cooled Fast Reactor (GFR) after a Loss of Coolant Accident (LOCA) [2].

1. Introduction

Modern nuclear reactor concepts make use of passive safety features, which do not need external input (especially energy) to operate [3] and, thus, are expected to improve the safety of nuclear power plants because of simplicity and reduction of both human interactions and hardware failures [4–6].

However, the *aleatory* and *epistemic* uncertainties involved in the *operation* and *modeling* of passive systems are usually larger than for active systems [7,8]. Due to these uncertainties, the physical phenomena involved in the passive system functioning (e.g., natural circulation) might develop in such a way to lead the system to fail its function (e.g., decay heat removal): actually, deviations in the natural forces and in the conditions of the underlying physical principles from the expected ones can impair the function of the system itself [9–21]. In the analysis of such *functional failure* behavior [10], the passive system is modeled by a mechanistic Thermal–Hydraulic (T–H) code and the probability of failing to perform the required function is estimated based on a Monte Carlo (MC) sample of code runs which propagate the uncertainties in the model and numerical values of its parameters/variables [22–38].

Within this framework, the objective of sensitivity analysis is twofold: (i) the determination of the contribution of the individual uncertain parameters/variables (i.e., the inputs to the T–H code) to the uncertainty in the outputs of the T–H model code; (ii) the quantification of the importance of the individual uncertain parameters/variables in affecting the performance (i.e., in practice, the functional failure probability) of the passive system [39–41]. In this view, the sensitivity analysis outcomes provide two important insights. On the one side, the analyst can identify those parameters/variables that are not important and may be excluded from the modeling and analysis; on the opposite side, the analyst is able to identify those parameters/variables whose epistemic uncertainty plays a major role in determining the functional failure of the T–H passive system: consequently, his/her efforts can be focused on increasing the state-of-knowledge on these important parameters/variables and the related physical phenomena (for example, by the collection of

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doi:10.1016/j.ress.2011.08.006

experimental data one may achieve an improvement in the state-of-knowledge on the correlations used to model the heat transfer process in natural convection, and a corresponding reduction in the uncertainty) [30,38]. In the present context of passive system functional failure probability assessment the attention will be mainly focused on this latter aspect, i.e., the identification of those uncertain variables playing a key role in the determination of the passive system performance.

In all generality, approaches to sensitivity analysis can be either *local* or *global*. As the name suggests, local methods consider the variation in the system model output that results from a local perturbation about some *nominal* input value. In the limit view, the sensitivity measure of the contribution of a generic uncertain input parameter to the uncertainty of the output is the *partial derivative* of the output with respect to the input parameter itself calculated around the nominal values of the input parameters. Such measure identifies the critical parameters as those whose variation leads to the most variation in the output [39,42]. On the contrary, global techniques aim at determining which of the uncertain input parameters influence the output the most when the uncertainty in the input parameters is *propagated* through the system model [43]. In this view, the term "global" has two meanings: the first one is that, for one input parameter whose uncertainty importance is evaluated, the effect of the *entire* uncertainty distribution of this parameter is considered; the second one is that the importance of this input parameter should be evaluated with *all* other input parameters varying as well [44]. Examples of methods for global sensitivity analysis include the so-called *variance-based* techniques (such as those relying on the computation of Sobol indices [1,39,44–46] or the Fourier Amplitude Sensitivity Test (FAST) [47]) and the more recent *moment independent* techniques [43,48–52]. The interested reader may refer to [39,42,53–58] for detailed and updated surveys on sensitivity analysis methods.

Regardless of the technique employed, sensitivity analysis relies on *multiple* (e.g., many hundreds or thousands) evaluations of the system model (code) for different combinations of system inputs. This makes the associated computational effort very high and at times prohibitive in practical cases in which the computer codes require several hours (or even days) to run a single simulation [32,59].[1] Further, in the present context of nuclear passive systems, the computational issue is even more dramatic because the estimation of the functional failure probability is *also* of interest *besides* the sensitivity analysis of the passive system performance: as a consequence, the (typically, hundreds of thousands) simulations performed for estimating the functional failure probability have to be *added* to those carried out for the sensitivity analysis.

In light of the computational problem, the main objective of the present study is to show the possibility of efficiently *embedding* the sensitivity analysis of the performance of a nuclear passive system *within* the estimation of its functional failure probability, while resorting to a reasonably *limited* number of system model code evaluations. To this aim, the use of two advanced Monte Carlo Simulation (MCS) methods, namely Subset Simulation (SS) [60,61] and Line Sampling (LS) [62,63] is investigated.

In the SS approach, the functional failure probability is expressed as a product of conditional probabilities of some chosen intermediate events. Then, the problem of evaluating the probability of functional failure is tackled by performing a sequence of simulations of these intermediate events in their conditional probability spaces; the necessary conditional samples are generated through successive Markov Chain Monte Carlo (MCMC) simulations [64], in a way to gradually populate the intermediate conditional regions until the final functional failure region is reached. Two approaches of literature are here considered for performing the sensitivity analysis of the passive system performance by SS: the first one is *local* and embraces the so-called concept of *reliability sensitivity*, in which the sensitivity of the performance of the passive system to a given uncertain input variable is quantified as the *partial derivative* of the system failure probability with respect to the parameters (e.g., the mean, the variance, etc.) of the probability distribution of the input variable itself [65]; the second one is *global* and employs the conditional samples generated by MCMC simulation to obtain the *entire distribution* of the system failure probability conditional on the values of the individual uncertain input parameters/variables [66,67].

In the LS method, lines, instead of random points, are used to probe the failure domain of the multi-dimensional problem under analysis. An "important vector" is optimally determined to point towards the failure domain of interest and a number of conditional, one-dimensional problems are solved along such direction, in place of the multi-dimensional problem [62,63]. In this approach, the sensitivity of the passive system performance to the uncertain system input parameters/variables can be studied through the examination of the elements of the LS important vector pointing to the failure region: a *local* informative measure of the relevance of a given uncertain variable in affecting the performance (i.e., in practice, the functional failure probability) of the passive system is the magnitude of the corresponding element in the LS important vector [68–71].

The SS- and LS-based approaches to sensitivity analysis are tested on two case studies: the first one is based on the highly nonlinear and non-monotonous Ishigami function [1,39]; the second one involves the natural convection cooling in a Gas-cooled Fast Reactor (GFR) after a Loss of Coolant Accident (LOCA) [2]. The results obtained by the SS- and LS-based sensitivity analysis techniques are compared to those produced by *global* first- and total-order Sobol indices [39,45].

In synthesis, the main contributions of the present paper are the following:

- *applying* the SS and LS methods to *embed* the sensitivity analysis of the performance of a nuclear passive system *within* the estimation of its failure probability, while resorting to a reasonably *limited* number of system model code evaluations: to the best of the authors' knowledge, this is the first time that SS- and LS-based sensitivity analysis methods are applied to nuclear passive systems;
- *comparing* the results obtained by the following approaches to sensitivity analysis: (i) SS-based local and global (reliability) sensitivity analyses, (ii) LS-based local (reliability) sensitivity analysis and (iii) "classical" variance-based global sensitivity analysis relying on the computation of Sobol indices;
- *challenging* approaches (i)–(iii) mentioned above in problems where the failure region of the passive system is composed by *multiple*, *disconnected* parts.

The reminder of the paper is organized as follows. In Section 2, a snapshot on the functional failure analysis of T–H passive systems is given. In Section 3, the SS and LS methods here employed for efficiently embedding the sensitivity analysis of the performance of a nuclear passive system *within* the estimation of its functional failure probability are presented. In Sections 4 and 5, the case studies concerning the Ishigami function and the passive cooling of a

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[1] For example, the computer code RELAP5-3D, which is used to describe the thermal–hydraulic behavior of nuclear systems, may take up to twenty hours per run in some applications.