Annals of Nuclear Energy 55 (2013) 9–17

Contents lists available at SciVerse ScienceDirect

Annals of Nuclear Energy

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

Efficient estimation of the functional reliability of a passive system by means of an improved Line Sampling method

Baosheng Wang [a], Dongqing Wang [a], Jin Jiang [a,b,*], Jianmin Zhang [a]

[a] Department of Nuclear Science and Technology, Xi'an JiaoTong University, Xi'an, Shaanxi 710049, China
[b] Department of Electrical and Computer Engineering, The University of Western Ontario, London, Ontario N6A5B9, Canada

ARTICLE INFO

Article history:
Received 28 August 2012
Received in revised form 16 December 2012
Accepted 17 December 2012
Available online 19 January 2013

Keywords:
Functional failure reliability
Passive safety system
Uncertainty
Line Sampling
Important direction
Markov Chain

ABSTRACT

The Monte Carlo simulation based method requires considerable computational efforts for the estimation of functional reliability analysis. Efficient sampling techniques can be adopted for performing robust estimations with limited number of samples and associated with computational time. An innovative reliability analysis method known as improved Line Sampling, which incorporates the quadratic response surface taken as a fast-running surrogate in replacement of a long-running thermal hydraulic system code to improve the computational efficiency, is presented for the functional reliability analysis. In the present method, the important direction pointing towards failure region is obtained from the simulated samples with Markov Chain, instead of the original design point in the standard normal space. Simultaneously, the simulated samples can be used to evaluate the functional failure probability with the response surface. This application is illustrated for the functional reliability estimation of a passive residual heat removal system due to the epistemic uncertainties. The numerical results demonstrate the high level of computational efficiency and excellent computational accuracy by comparison to direct Monte Carlo simulation and original Line Sampling based on design point simulation. The sensitivity, defined as the partial derivative of the failure probability with respect to the distribution parameter can help to identify the relative contribution of the individual parameter to output response and guide the optimization design.

1. Introduction

Innovative nuclear reactor design concepts make use of passive safety features (Marquès et al., 2005; Pedroni et al., 2010), which do not need external input (especially energy) to operate (IAEA, 1991). This is why it is excepted that passive safety systems combine among others the advantages of simplicity, reduction of human interaction (Prosek and Cepin, 2008), reduction or avoidance of external electrical power or signals, reduction or avoidance of hard of failures (Mathews et al., 2008).

Many passive systems rely on natural circulations, which have much weaker driving forces than their active parts. Therefore, it is important to consider fluid mechanics issues, as well as disturbances or changes in operating parameters. In summary, uncertainties involved in the actual operation and their modeling of passive systems are usually larger than those in active systems. Two different sources of uncertainties are usually considered in safety analysis: randomness due to intrinsic variability in the actual geometrical properties, material properties and the initial/boundary conditions, referred as aleatory uncertainty; incomplete knowledge due to lack of data on some underlying physical phenomena and translate in uncertainties in the models and parameters used to represent them, referred as epistemic uncertainty (Apostolakis, 1990; Secchi et al., 2008; Zio et al., 2010b).

Due to these uncertainties, there is always a nonzero likelihood that a physical phenomena involved in the passive systems fail to perform their intended functions, even if there is no hardware failure (Secchi et al., 2008). Hence, in order to assess the effectiveness of passive safety systems, it is necessary to quantify the reliability of such systems first. The unreliability of passive safety systems can have two aspects: malfunctions of systems/components, referred as hardware failure and absence of intended physical phenomena, referred to as functional failure (Burgazzi, 2003, 2004; Mathews et al., 2008; Fong et al., 2009; Zio and Pedroni, 2009a, b). The present paper mainly focuses on functional reliability analysis in passive systems.

Various methodologies have been developed for the evaluation of functional failure probabilities of passive systems, known as Reliability Evaluation of Passive Safety (REPAS) (D'Auria et al.,

---

* Corresponding author at: Department of Electrical and Computer Engineering, The University of Western Ontario, London, Ontario N6A5B9, Canada. Tel.: +1 519 6612111x88320; fax: +1 519 850 2436.

E-mail addresses: wang.baosheng@stu.xjtu.edu.cn (B. Wang), wang.dongqing@stu.xjtu.edu.cn (D. Wang), jjiang@eng.uwo.ca (J. Jiang), zhangjm@mail.xjtu.edu.cn (J. Zhang).

0306-4549/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.anucene.2012.12.015

2002; Jafari et al., 2003), and Reliability Methods for Passive Safety (RMPS) (Marquès et al., 2005; Bassi and Marquès, 2008), respectively. These methods have been applied to residual heat removal systems in light water reactors. Similar approach is used for decay heat removal systems in gas-cooled fast reactors (Pagani et al., 2005; Mackay et al., 2008; Zio and Pedroni, 2009b), very high temperature gas cooled reactors (Woo and Lee, 2009; Han and Yang, 2010) and sodium-cooled fast breeder reactors (Mathews et al., 2008, 2011; Arul et al., 2009, 2010). In these methods, a primary cause of the functional failure is assumed to be arising mainly from the existence of the uncertainties in the system modeling and input parameters. Consequently, the system cannot accomplish its required function. In these works, the passive system is modeled by a deterministic mathematical thermal hydraulic code. The uncertainties of the system model and input parameters are quantified by assigning appropriate probability density function (PDF) and the functional failure probability is estimated by a Monte Carlo simulation (MCS), which propagates the epistemic uncertainties in the model and the numerical values of its input parameters.

The MCS based approach provides in principle the most realistic assessment of the passive systems functional failure probability thank to the flexibility of the MCS, which does not suffer from any thermal hydraulic model complexity (Zio and Pedroni, 2009a,b). In practice, the functional failure probability of a passive system can be relatively low, so that a large number of samples are required to obtain a sufficient confidence level. Unfortunately, the computational cost is normally prohibitively high, if a direct MCS is used with a deterministic thermal hydraulic model code (Schueller, 2007). To reduce the computational time, efficient sampling techniques can be adopted to perform functional reliability estimations of passive systems.

In this paper, an improved simulation approach called as Line Sampling (LS), which can efficiently evaluate reliability in such a high dimensional problem of structural reliability analysis, is adopted (Koutsourelakis et al., 2004; Pradlwarter et al., 2005). The basic idea is to employ lines, instead of random points, to probe the failure region of multidimensional setting. An important direction $\boldsymbol{\alpha}$ is optimally determined to point towards the failure region F and a number of conditional, one-dimensional problems are solved along such direction, in place of the high-dimensional problem (Pradlwarter et al., 2005; Zio and Pedroni, 2009b, 2010a). However, two main issues are still under research: first, long computer times are necessary for each run of thermal hydraulic code; second, the important direction is not easy to be searched as the limit sate function is implicit, which requires additional runs resulting in computational time increasing. This work is an attempt to resolve the two main issues to improve computation efficiency for the functional reliability analysis of passive systems by first: a fast-running, surrogate model called response surface (RS) in replace of the long-running thermal hydraulic code; second, an optimal important direction based on Markov Chain procedure for determining the important direction in the failure region. The advantage of this method is demonstrated and applied in a functional reliability analysis of a passive residual heat removal system.

A sensitivity analysis, which concerns with ranking of the individual uncertainty parameters according to their relative contributions on the functional failure probability, has been carried out. In this case, an alternative approach is applied to identify and rank influential individual uncertainty parameters based on the sensitivity of the cumulative distribution function (CDF) of the functional failure probability. The approach doesn't assume a linear or other explicit functional relationship between the response and the input parameters, and provide more information than the traditional regression-based methods. The sensitivity coefficient is expressed as an expectation of the partial derivative of the failure probability with respect to the distribution parameter.

The remainder of paper is organized as follows. In Section 2, the passive safety systems functional failure reliability methodology is depicted. The functional reliability analysis method of improved LS procedure is provided in Section 3. In Section 4, the application concerning a passive residual heat removal system (PRHRS) of a 1000 MWe Pressurized Water Reactor (PWR) is illustrated during a station blackout transient. The functional failure probability estimation by the improved LS method and comparison of results DMCS, and the original LS method is described in Section 5. The sensitivity analysis is carried out to determine the contributions of individual uncertain parameters in Section 6 and some conclusions are given in the last Section.

2. Functional reliability analysis of passive safety systems

In the reliability analysis of a passive thermal hydraulic system, the probability that the corresponding response variable (e.g. coolant outlet temperature at critical location) exceeds the threshold value is termed as the functional failure probability. A procedure for the evaluation of the functional failure probability has been proposed known as RMPS methodology. The organization of the methodology for the evaluation of the functional reliability is depicted in Fig. 1. The basic steps of the functional reliability analysis of passive safety systems are as follows (Marquès et al., 2005; Zio and Pedroni, 2009a,b; Arul et al., 2010):

1. Detailed modeling for the passive safety system by deterministic thermal–hydraulics code.
2. Identification of the uncertainty relevant parameters/variables in passive safety systems.
3. Quantification of appropriate probability density functions to these parameters/variables.
4. Evaluation of the failure criteria for the passive system on basis of its function.
5. Construction a response surface model as fast-running surrogate of the long-running code.
6. Propagation the epistemic uncertainties with the response surface model by using the improved LS method.
7. Quantification of functional failure probability, Let $\boldsymbol{X} = \{x_1, x_2, \cdots, x_n\}$ be the vector of the uncertainty parameters, $Y(\boldsymbol{X})$ be the indicator of the performance of passive system, A_Y be the threshold value defining the failure criterion. By introducing a variable called Limit State Function (LSF) as $g(\boldsymbol{X}) = Y(\boldsymbol{X}) - A_Y$, failure occurs if $g(\boldsymbol{X}) < 0$. The system failure probability P_f can be evaluated by the following integral: $P_f = \int \cdots \int_{g(X)<0} f_X(\boldsymbol{X}) dx_1 \cdots dx_n$, where $f_X(\boldsymbol{X})$ is the joint probability density function, and
8. Determination of the contribution of each uncertainty parameter via parametric sensitivity analysis.

Within this conceptual framework, various computational methodologies are considered to efficiently estimate the functional reliability of passive safety systems. This study attempts to improve the computational efficiency in the evaluation functional failure probability of a passive residual heat removal system of China's 1000 MWe PWR design by including modeling of the system, uncertainty propagation, functional failure probability estimation and sensitivity analysis.

3. Methodology for the improved Line Sampling

LS is a stochastic method for efficiently estimating multidimensional and low failure probability, originally developed for the reliability analysis of structural systems (Koutsourelakis et al., 2004; Pradlwarter et al., 2005; Zio and Pedroni, 2009b, 2010a). The efficiency depends on the determination of the impor-