Nuclear Engineering and Technology 48 (2016) 765–772

Available online at ScienceDirect

Nuclear Engineering and Technology

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

Original Article

On-the-fly Estimation Strategy for Uncertainty Propagation in Two-Step Monte Carlo Calculation for Residual Radiation Analysis

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ARTICLE INFO

Article history:
Received 5 October 2015
Received in revised form 28 December 2015
Accepted 15 January 2016
Available online 2 February 2016

Keywords:
Error Propagation
On-the-fly
Monte Carlo
Residual Radiation
Stochastic Uncertainty

ABSTRACT

In analyzing residual radiation, researchers generally use a two-step Monte Carlo (MC) simulation. The first step (MC1) simulates neutron transport, and the second step (MC2) transports the decay photons emitted from the activated materials. In this process, the stochastic uncertainty estimated by the MC2 appears only as a final result, but it is underestimated because the stochastic error generated in MC1 cannot be directly included in MC2. Hence, estimating the true stochastic uncertainty requires quantifying the propagation degree of the stochastic error in MC1. The brute force technique is a straightforward method to estimate the true uncertainty. However, it is a costly method to obtain reliable results. Another method, called the adjoint-based method, can reduce the computational time needed to evaluate the true uncertainty; however, there are limitations. To address those limitations, we propose a new strategy to estimate uncertainty propagation without any additional calculations in two-step MC simulations. To verify the proposed method, we applied it to activation benchmark problems and compared the results with those of previous methods. The results show that the proposed method increases the applicability and user-friendliness preserving accuracy in quantifying uncertainty propagation. We expect that the proposed strategy will contribute to efficient and accurate two-step MC calculations.

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http://dx.doi.org/10.1016/j.net.2016.01.009

1. Introduction

Particle transport analyses are preformed to get responses (i.e., dose rate, flux, criticality, and power distribution) in a system. The Monte Carlo (MC) method, which is stochastic, is accurate. Therefore it is widely used in the particle transport and analysis fields. The MC approach calculates an average and uncertainty of the responses by its stochastic processes. The uncertainty of the response confirms the reliability of the response; thus, analyzers can directly use it to determine design parameters, design limits, and so on when using the MC method as an analysis tool.

Serial MC simulations might be required to analyze the particle transport phenomenon, such as fuel depletion calculations, the source term generation problem, i.e., the standby service water (SSW)–specific safety requirements (SSR) option in MC N-particle (MCNP) [1], and residual radiation analysis from activated materials [2]. The problem in using serial MC simulations is an inability to accurately evaluate the uncertainty. Usually, for such problems, researchers just use the average value of response estimated from the previous MC calculation as the input for the next calculation. As a result, the uncertainty computed in the last MC calculation is underestimated because it does not consider the stochastic uncertainty generated in previous steps. Thus, to obtain reliable results, researchers need to properly quantify the uncertainty propagation caused by input uncertainty that occurs as a result of previous MC calculations.

The brute force technique [3] analyzes uncertainty propagation by repetitive MC calculations using the same input with different random seeds. Statistically analyzing the results produces the sample standard deviation and it is taken to be the true stochastic uncertainty. The method is accurate because its analysis well reflects the stochastic nature of previous MC calculations. However, the computational cost can be extremely high because it requires a huge number of MC calculations to achieve reliable results for a complex problem.

To prevent this inefficiency, the Oak Ridge National Laboratory proposed an adjoint-based method using an error propagation formula [4]. The method derives a relationship between the true stochastic uncertainty and the uncertainty computed from the previous MC calculation. After estimating the adjoint flux, the method calculates the true uncertainty. It has an advantage in estimation efficiency over the brute force method because it requires only one additional adjoint calculation. However, it has the following limitations and difficulties: (1) it assumes the covariance term in the derived equation to be zero; and (2) it requires an additional calculation to obtain the adjoint flux.

To overcome the limitations of previous methods, we propose a new on-the-fly estimation strategy for the true stochastic uncertainty of the two-step MC calculations to improve both efficiency and accuracy. The main idea of the proposed approach is that it estimates the information required to analyze uncertainty propagation by adopting importance estimation and covariance of source-term estimation in forward MC calculations [5]. In Section 2, we describe the proposed method in detail. In Section 3, we verify the proposed method using activation benchmark problems.

2. Materials and methods

Here, we briefly introduce the previously published methods to analyze error propagation. In Section 2.3, we describe our proposed strategy to estimate error propagation.

2.1. Overview of the brute force method

Fig. 1 illustrates a procedure for the brute force method. First, a seed number is randomly sampled for each simulation. Then, a two-step MC simulation is performed with the random seed numbers until the responses have a reliable distribution. After analyzing the type of response distribution from the MC simulations, the true uncertainty is defined as the sample standard deviation of the responses. This method can analyze uncertainty propagation without any assumptions. However, the calculation efficiency is low because of the repetitive procedure.

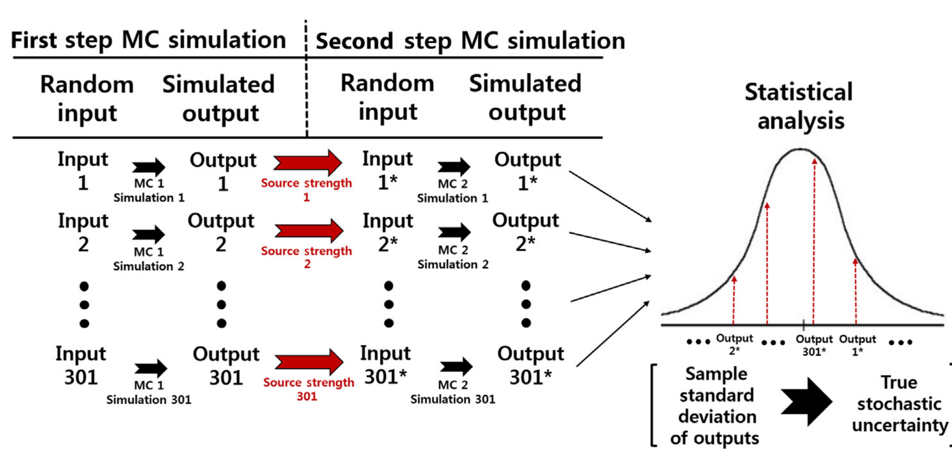

Fig. 1 – Procedure for the brute force technique in a two-step Monte Carlo calculation. MC, Monte Carlo.