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A new global variance reduction technique based on pseudo flux method

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ABSTRACT

In radiation shielding problem as well as nuclear reactor analysis applications, Monte Carlo (MC) method is considered as the most useful tool for its obvious advantage to deal with heterogeneous and complex system model. However, for the deep-penetration problem in shielding calculation, analog MC method is inefficient since particles have little contribution to the estimators in far-source region. Numerous variance reduction techniques have been proposed to improve the calculation efficiency such as the importance sampling and weight window (WW) technique. But these techniques still cannot realize global variance reduction. In this paper, a new pseudo flux method is proposed to realize global variance reduction. It based on forward MC calculation by MCNP and does not need secondary modeling and much implement to MC code. Forward particle flux and relative error (Re) are used to form WW thresholds. The empty mesh cells which unsampled in far-source region would lead to zero WW thresholds. The zero transport parameters have a significant influence on the calculation efficiency. The pseudo flux method based on direct contribution algorithm of point detector flux estimation is used to form pseudo flux as the unsampled tally value. This method would improve the calculation efficiency substantially and accelerate convergence. From the numerical test calculations, the Re distribution was flattened in whole phase region and empty mesh rate was reduced. The efficiency was considered to be better than analog simulation by comparing figure-of-merit (FOM) values. The goal of global variance reduction has been achieved. The proposed method based on forward MC estimates and pseudo flux could be useful variance reduction techniques in MC deep-penetration calculation.

1. Introduction

In three-dimensional shielding calculation, Monte Carlo (MC) method is considered as the most accurate method for radiation transport calculation. It has been widely used due to the obvious advantages of dealing with heterogeneous, large scale complex system model and accurate source definition. In MC simulation, individual particles are simulated by tracking their life histories, and events and information are recorded to obtain their average behaviors which are scored as tallies. However it is a difficult task to accomplish the deep-penetration calculation with reasonable convergence accuracy because particles have little chance to transport into the far-source tally region. Numerous variance reduction techniques have been put forward to accelerate MC simulation (Booth et al., 2012). Currently, the most useful and efficient variance reduction techniques are weight window and Russian roulette and splitting.

For global variance reduction (GVR) problems, the whole geometry is considered equal important and mesh tallies over the entire phase space with uniform relative error to converge each mesh simultaneously are desired. However these available variance reduction techniques may still inefficient and even invalid to flatten the spatial relative error distribution. Based on the forward estimates by MCNP, the particle flux and relative error information are used to calculate weight window thresholds as transport bias parameters. For the empty mesh cells which no particles have been tracked, it's difficult to guess a reasonable flux value. In the paper a new pseudo flux method based on direct contribution algorithm of point detector flux estimation was proposed to calculate pseudo flux for unsampled mesh cells by a deterministic way. The pseudo flux is used to form thresholds for empty meshes, thus approximate weight window parameters are applied in deep penetration zone. The Nestor Shielding and Dosimetry Improvement Program (NESDIP-2) benchmark has been used to validate the efficiency of the methods described in this work.

The remainder of this paper is organized as follows. Section 2 gives the descriptions of theoretical basis of this paper. Section 3 describes the global variance reduction methods based on forward MC estimates and pseudo flux method. The application and verification of variance reduction methods are shown in Section 4. The results and discussions

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are presented in Section 5. The Section 6 gives the conclusions.

2. Background

2.1. LVR and GVR

In MC simulation, the problems are summarized as i) Source-Detector (S-D): Single detector response, ii) Source-Region (S-R): Flux/Response over a portion of the problem, iii) Global problem: Flux/Response over the entire problem space (Peplow, 2012). For local variance reduction (LVR) in S-D problem only one response tally is needed and in S-R problem a portion tallies in regions of interest are required. Numerous variance reduction techniques have been applied in S-D and S-R problem successfully such as exponential transform and implicit capture etc. For global variance reduction in a global problem, the whole phase space is considered equal important and should be uniform sampled. The spatial distribution of relative error in whole region should as flat as possible. Many methods based on importance sampling and weight window have been put forward to realize the GVR (Peplow, 2012).

2.2. Weight window technique

One of the most important variance reduction techniques used in GVR is weight window (Booth and Hendricks, 1982). The objective of weight window is control the particle weight. High-weight particles split and more information is collected per history. Low-weight particles are rouletted, so computation time is not wasted following particles of trivial weight and more history can be run in fix computer time. An upper and lower weight window bound can be specified by weight window generator or user for each mesh cells. If particle weight is below the lower weight threshold, Russian roulette would be played. The particle weight is either increased to a value within the window or the particle is terminated with a certain probability. If particle weight is above the upper weight bound, particle would be split so that all the particles weight are within the window. By using this technique, more time would be spent on sampling in important regions or important particles. However, the parameters of weight window and importance functions usually depend on user's experience.

The weight window parameters are estimated by weight window generator (WWG) according to Eq. (1) and it is inverse proportional to the importance function. If the threshold is set as zero, then the weight window technique would be turned off and no Russian roulette and splitting would be played. According to Eq. (1), the importance parameters are also obtained from statistical estimates. However, unless particles actually reach the tally region or a phase space region is sampled adequately, there will be either no importance parameters generated or an unreliable one. Moreover, several iterations are needed to get an optimum importance function for a certain tally.

$$\text{Importance} = \frac{\text{Total score due to particles and their progeny entering the cell}}{\text{Total weight entering the cell}} \quad (1)$$

2.3. GVR based on adjoint estimates

Many scholars have put forward several variance reduction methods which have been applied in deep-penetration shielding calculation successfully. One of the most successful methods is employing adjoint information to accelerate convergence which is considered as the most prospect variance reduction technique to realize GVR (Kendra and Larsen, 2015; Zhang and Abdel-Khalik, 2014). Adjoint flux means the contribution of source neutron to a target tally, moreover it also can be considered as the importance of a neutron. According to these, the adjoint information can be used as the importance map to bias the important neutron to the region of interest. Zero variance reduction theory has been proposed almost along with the Monte Carlo method. There is only one possible zero variance reduction scheme with source bias and transport bias. However zero variance reduction is quite difficult because if the exact adjoint function is known, a perfect MC simulation can be achieved. Actually, it's impossible to obtain the exact adjoint function theoretically. An approximate zero variance reduction simulation can be achieved by using the bias parameters from the approximate adjoint functions. Deterministic method is usually used to adjoint calculation.

Wagner (Wagner et al., 2014; Haghighat and Wagner, 2003) and Becker (Becker, 2009; Becker and Larsen, 2009) have applied this method to variance reduction successfully. They use forward calculation to compute forward flux and construct the adjoint source through the forward estimates. The adjoint calculation is the inverse operation of forward calculation. Set the adjoint source as the source of adjoint calculation and operate the adjoint calculation to get the adjoint flux in whole phase space for GVR. Then construct the weight window and source bias parameters by the adjoint information. By coupling the MC method and discrete ordinates (SN) method, the efficiency of MC simulation can be improved substantially and Re distribution of whole region would be flattened.

2.4. GVR based on forward estimates

The main purpose of GVR is to obtain a uniform Monte Carlo particle distribution over entire region, which would lead to approximate uniform tally convergence. Cooper and Larsen (2001) proposed that it's possible to use forward deterministic estimates to obtain the weight window parameters. The weight window is set proportional to forward flux and normalized to the maximum flux $\phi(r)$. Becker and Larsen (2009) expanded Cooper's method to a function of space and energy. Forward discrete ordinates estimates of flux $\phi(r, E)$ are also used to construct weight window. By coupling SN and MC method, GVR can be achieved. However secondary modeling is needed for SN simulation and it may time-consuming especially for fine complex model. The geometry simplification may also bring uncertainties. The mesh definition of SN calculation and MC weight window may not coincide with each other.

Van Wijk et al. (2011) and Davis and Turner (2011) show that it is possible to use a MC forward estimation to form the weight window thresholds, and it does not require any secondary models or many codes. However, MC forward estimation may lead to unreliable results or unsampled mesh cells. These inaccurate estimates would affect the simulation efficiency and sometimes iterative calculation schemes are needed to realize GVR. Fan (Fan et al., 2016) use the minimum flux of the mesh tally as the empty mesh cells flux. However, the weight window thresholds in empty mesh cells are the same by using the minimum flux. Particles in these same weight window would not roulette and split. And the calculation efficiency cannot be further improved.

3. Method descriptions

3.1. GVR based on forward simulation

3.1.1. GVR based on flux estimates

In GVR, the whole phase space is considered equal important and the relative error distribution should be as flat as possible. In ideal conditions, we expect the particle density is uniform and every mesh cells are uniform sampled. To get a flat Re distribution, we assume the particle density $D(r)$ is uniform in whole region. That is,

$$D(r) = C \quad (2)$$

C is a constant. Each particle has a average weight $\overline{w}(r)$, and the Monte Carlo particle flux is equivalent to the $D(r)$ and weight $\overline{w}(r)$. We