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A new local variance reduction method based on anti-forward Monte Carlo calculation

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ABSTRACT

Monte Carlo (MC) method is widely used in radiation shielding calculations with the advantages of high fidelity geometry modeling, complex radiation source description and continuous-energy cross sections. The deep-penetration problem prevents the further application of MC method in radiation transport calculation. It is difficult to obtain reliable results for a certain tally due to the poor particle statistics. Thus, effective local variance reduction (LVR) technique must be applied to bias particles toward tally region. In this paper, combined with weight window technique, a new local variance reduction method based on anti-forward calculation has been proposed. The detector tally in forward run is set as source position in anti-forward run. Anti-forward calculation flux has been used to construct weight window parameters. From the numerical test calculations, a speedup of 420 times has been achieved compared to the analog simulation. More computational time has been spent on one Monte Carlo source particle, but more tally information has been collected. The goal of local variance reduction has been achieved. The proposed local variance reduction technique could be a useful tool in MC deep-penetration shielding calculation.

1. Introduction

With the development of computer science and nuclear energy system, Monte Carlo (MC) method is considered as the most useful tool in radiation transport calculation. It can model the fine geometry and complex source exactly. However, the deep-penetration problem prevents the application of MC method in large scale system simulation. When the geometry size is dozens times than particle mean free path, particles have little chance transported to the far-source area. The statistics error may be large and the tally results may be questionable. Accordingly, effective variance reduction techniques are needed to accelerate the result convergence (Martin, 2007).

In MC simulation, the variance reduction techniques are summarized as global variance reduction (GVR) technique and local variance reduction (LVR) technique (Peplow, 2012; Shi et al., 2017c). Numerous variance reduction methods have been proposed which have been implemented to MC code and applied in shielding calculation to realize GVR and LVR successfully (Booth et al., 2012a; Fan et al., 2016; Zhao et al., 2016; ShangGuan et al., 2016; Shi et al., 2017a,b,c). For GVR, the whole geometry is considered as equal important and the statistics error of all tallies should be small. Many scholars proposed that couple discrete ordinates (SN) method and MC method could realize GVR (Wagner et al., 2014, 2015; Becker, 2009, Becker and Larsen, 2009; Solomon et al., 2010; Avneet et al., 2009; Wu and Abdel-Khalik, 2013; Zhang and Abdel-Khalik, 2014; Cooper and Larsen, 2001). For LVR, only one response tally (source-detector problem) or a portion tallies in region of interest (source-region problem) are required. Compared to the GVR method, the LVR method is more useful in practical applications (Murata et al., 2008; Li et al., 2011). The GVR method use source bias and transport bias to distribute the Monte Carlo particles and computational resource uniformly. Thus, each phase space can obtain accurate tally results simultaneously. Although we can realize LVR though GVR method, the computational resource would waste in non-statistics area. The calculation may inefficiency. Therefore, for source-detector problem and source-region problem, special local variance reduction method is needed to bias the particles to the single tally.

Weight window technique which based on forward calculation is one of the most effective variance reduction methods. It provides an importance function for specifying space and energy. The objective of weight window is control the particle weight during transport. High-weight particles split and more information is collected per history. Low-weight particles are rouletted, calculation time would not be wasted following particles of trivial weight and more history can be run in fix computer time. Thus, more Monte Carlo

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particles are biased to the tally area and more computational resource is spent on the region of interest. The weight window parameters are estimated by weight window generator (WWG) according to Eq. (1) (Briesmeister, 1993).

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

According to Eq. (1), the importance parameters are obtained from statistical estimates. Unless particles actually reach the tally region or the tally 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.

The essence of weight window generator is establishing a threshold gradient, let Monte Carlo particles transport to the weight window threshold decrease direction. Monte Carlo particles and computational resource always trend to flow to the maximum threshold gradient decrease direction. If the tally area is the terminal point of the maximum threshold gradient decrease direction, most of the Monte Carlo particles in system would be biased to that tally area. The statistics sample would increase and the tally results would become reliable. Therefore, the key of using weight window technique to local variance reduction is how to establish an optimal weight window threshold gradient to bias the Monte Carlo particles and computational resource to the target tally area.

In this work, a new local variance reduction method based on anti-forward Monte Carlo calculation has been proposed. It introduces an approximate optimal weight window threshold gradient construction method for LVR. The Winfrith Iron benchmark experiment (ASPIS) has been used to validate the efficiency of described method. By using the LVR method, the goal of local variance reduction has been achieved.

The remainder of this paper is organized as follows. Section 2 gives the LVR method description in this paper. The application and verification of LVR method are discussed in Section 3. The results and discussion are presented in Section 4. Section 5 gives the conclusions.

2. Methods

In isotropic source case, Monte Carlo particles start from the forward source and transport to each corner of the system. However, only a few particles could be transported to the detector area. Most particles are useless and have no contribution to the detector tally. It wastes amount of calculation time and computational resource. In shielding calculation, the particle flux decreases along the shield depth and the flux distribution is just like the "contour line". This flux "contour line" constructs a gradient and the forward source locates the center. Several scholars use this "contour line" flux distribution to construct weight window parameters to realize GVR (Davis and Turner, 2011; Van Wijk et al., 2011; Shi et al., 2017a,b,c). These weight window parameters could bias particles and computational resource to the flux decrease direction region and make the Monte Carlo particles uniformly distributed in the system.

For LVR, special weight window thresholds are needed to bias the Monte Carlo particles to the detector area. A new local variance reduction method based on anti-forward Monte Carlo calculation (AFLVR) has been proposed. The calculational scheme of AFLVR is shown in Fig. 1. In AFLVR, define the source position in anti-forward calculation by the forward calculation tally position. And mesh tally all the geometry model. The flux in anti-forward source area is large. Along the shield depth, it decreases in all direction. Thus, the flux "contour line" constructs a gradient distribution. Use the minimum flux of all mesh tallies to divide the flux to obtain weight window threshold parameters as Eq. (2). If the flux is zero, the threshold would be set as zero. Particles in zero weight window would transport in analog way. And computational time would not be wasted in these particles. The weight window threshold of anti-forward model source region is minimum. If these weight window parameters are applied in forward run, particles would be biased to the anti-forward model source area. The AFLVR method would only need one geometry model compared to the MC and discrete ordinates (SN) coupled method which needs two full-scale models. The mesh definition of mesh tally and weight window could consistent with each other completely. But the AFLVR method needs to construct the anti-forward model. Compared to the weight window generator in MCNP, it may cumbersome in some complex system. By using these weight window parameters, the local variance reduction could realize.

However, the weight window thresholds in forward source area may several orders lower than source birth weight. The default source particle birth weight is set as one. Then, particles would split after birth. Such harsh splitting may increase the calculation time enormously. In order to ensure the source particle weight in the weight window, the source birth weight must be adjusted. According to Eq. (3), the source distribution should be also adjusted to guarantee the tally results unbiased. The source bias parameters are defined by Eq. (4). A smooth index ($SI \in 0\text{–}1$) is used to avoid harsh splitting and Russian roulette (Booth, 2012b). The detail calculation steps are shown as below.

$$w_{th}(r,E) = \begin{cases} \left(\frac{\phi_{min}(r,E)}{\phi(r,E)}\right)^{SI}, \phi(r,E) \neq 0 \\ 0, \phi(r,E) = 0 \end{cases} \quad (2)$$

$$w_0 \cdot Q_0 = w_{bias} \cdot Q_{bias} \quad (3)$$

$$Q_{bias} = Q_0 \cdot \left(\frac{\phi(r,E)}{\phi_{min}(r,E)}\right)^{SI} \quad (4)$$

w_{th} is the weight window threshold, ϕ_{min} is the minimum flux of mesh tallies, ϕ is the flux of mesh tallies, r is position and E is energy. w_0 (equal to 1) and Q_0 are the unbias source weight and source distribution. w_{bias} and Q_{bias} are the bias source weight and source distribution.

Step 1. Generation of anti-forward model

According to the forward model, exchange and redefine the source and tally region. The source position in anti-forward run is defined in the tally zone of forward calculation. The energy of source particle may be set a little large. Keep the geometry model invariant.

Step 2. Generation of weight window parameters

Mesh plots the geometry model. Fine meshing for important target region and coarse meshing for unimportant region. The mesh tally definition and weight window generator mesh definition should consistent with each other completely. Perform anti-forward MC calculation, obtain the flux distribution and generate a WWOUT file which contains the weight window mesh definition and energy boundary information. Obtain the bias parameters according to Eqs. (2) and (4).