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Application of a global variance reduction method to HBR-2 benchmark

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ABSTRACT

It is a great challenge to obtain reliable results in reasonable time by the Monte Carlo (MC) method in solving the deep-penetration shielding problem. Based on Discrete Ordinate (SN) fluence rate, local and global variance reduction (LVR and GVR) methods use the biased source and weight window technique to decrease MC calculation tally error for the deep-penetration problem. This paper analyses calculation efficiency of the LVR and GVR methods for the HBR-2 benchmark. Numerical results show that both the LVR and GVR methods obtain reliable results for the HBR-2 benchmark. The LVR method requires separate SN and MC calculation for each dosimeter; whereas the GVR method simultaneously optimizes both in-vessel and ex-vessel dosimeters using an adjoint source weighted by SN forward response. The application of the GVR method is more efficient and convenient than LVR method.

1. Introduction

As one of the important methods in reactor shielding calculation, Monte Carlo (MC) method has advantages of fine geometrical modeling and accurate cross section processing. Neutron fluence rate decreases several orders from reactor core to outside because of the large dimension and complex structure of reactor. Reactor shielding calculation has the feature of deep-penetration, requiring a prolonged calculation process. Based on the Discrete Ordinate (SN) fluence rate, local variance reduction (LVR) method and global variance reduction (GVR) method decrease MC calculation tally error of deep-penetration problem using biased source and weight window (WW) (Haghighat and Wagner 2003, Peplow et al., 2008, Wagner et al., 2009). Biased source generates more source particles in important phase space than unbiased source does. WW performs splitting or roulette to particles according to space or energy related importance, which increases number of particles reaching important phase space. The consistent adjoint driven importance sampling (CADIS) method/Forward-CADIS (FW-CADIS) method adopted in SCALE's MAVRIC sequence is one of the most successful LVR/GVR methods (Peplow, 2011). MAVRIC uses the DENOVO code (Evans et al., 2010) to compute coarse-mesh discrete ordinates solutions that are used by CADIS/FW-CADIS to form an importance map and biased source distribution for the MONACO Monte Carlo code.

HBR-2 reactor pressure vessel (RPV) benchmark intends to validate the capabilities of the calculation method to predict the specific activities of the dosimeters irradiated in a surveillance capsule (in-vessel) and in a cavity detector well (ex-vessel) (Remec and Kam, 1997). LVR method requires separate calculation to obtain results with reliable tally error because the in-vessel dosimeter and ex-vessel dosimeter are separated by RPV with 20 degree apart. This paper applies a GVR method based on SN fluence rate to the HBR-2 benchmark to optimize tallies at different locations simultaneously by one calculation.

The differences between the variance reduction method in this paper and the CADIS/FW-CADIS method in MAVRIC sequence include the following points: 1) This paper calculates a three-dimensional (3D) pin-by-pin source distribution from pin power whereas it is difficult to specify a 3D pin-by-pin source distribution by MAVRIC even with the mesh source file. 2) In MAVRIC sequence, neutron and photon coupling problems are divided into several separate neutron and photon calculations. Separate calculation of neutron and photon will decrease the efficiency of the CADIS/FW-CADIS methods. This paper develops a new source subroutine for JMCT, a 3D neutron-photon transport Monte Carlo code (Deng, 2014), to simulate and optimize neutron and photon coupling calculation at the same time (Zheng et al., 2018). 3) This paper introduces a smooth factor ($0 < f \leqslant 1$) to alleviate violent change of the adjoint fluence rate. This method avoids excessive particle splitting/roulette and increases calculation efficiency. 4) At present DENOVO in MAVRIC only supports XYZ geometry while JSNT in this paper, a 3D multi-group parallel neutron-photon transport Discrete Ordinate code (Cheng et al., 2015), supports both XYZ and RθZ geometry.

The remainder of this paper is organized as follows. Section 2 shows the LVR and GVR methods, including the source bias factor, source particle weight and WW lower bound calculation method, and the

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flowchart of GVR. The application of the LVR and GVR methods to the HBR-2 benchmark is provided in section 3. The results and discussion are presented in section 4, including source bias and WW parameters, spectrum, reaction rate and specific activity. Calculation efficiency of both LVR and GVR methods are also compared in this section. Finally we draw some conclusions in Section 5.

2. Methods

2.1. Local variance reduction

2.1.1. Source bias factors

Detector response R is calculated by integrating forward source S and adjoint fluence rate ϕ^+ over the volume of forward source:

$$R = \int_{V_s}\int_0^{\infty} S(r,E)\phi^+(r,E)dEdr \tag{1}$$

Where r is space, E is energy, R is detector response, S is forward source, particle/(cm^3·s), ϕ^+ is adjoint fluence rate, V_s is volume of forward source, cm^3.

From Eq. (1) we can see that adjoint fluence rate stands for the contribution of forward source to detector response, therefore forward source S is biased by adjoint fluence rate ϕ^+ to obtain biased source $\hat{S}$:

$$\hat{S}(r,E) = S(r,E)\phi^+(r,E) \tag{2}$$

Where $\hat{S}$ is biased forward source, particle/(cm^3·s).

Transform Eq. (2) into discrete form, biased source with particle type is obtained:

$$\hat{S}(q,g,p) = S(q,g,p)\phi^+(q,g,p) \tag{3}$$

Where q is source mesh number, g is group number, p is particle type number, $p = 1$ is neutron, $p = 2$ is photon.

A smooth factor ($0 < f \leqslant 1$) is introduced to alleviate violent change of the adjoint fluence rate. This method avoids excessive particle splitting/roulette and increases calculation efficiency.

$$\phi^+(q,g,p) = [\phi^+(q,g,p)]^f \tag{4}$$

Where f is smooth factor.

Biased source generates more source particles in important phase space than unbiased source does. In order to calculate biased source distributions, source bias factors are introduced and calculated by summing up adjoint fluence rate. Energy bias factor is calculated by summing up space variable:

$$T(g,p) = \sum_{q=1}^{Q} \phi^+(q,g,p) \tag{5}$$

Where T is energy bias factor, is number of source mesh.

Space bias factor is calculated by summing up energy variable:

$$B(q,p) = \sum_{g=1}^{G(p)} \phi^+(q,g,p) \tag{6}$$

Where B is space bias factor, G is number of groups.

Particle type bias factor is calculated by summing up space and energy variables:

$$R(p) = \sum_{g=1}^{G(p)}\sum_{q=1}^{Q} \phi^+(q,g,p) \tag{7}$$

Where R is particle type bias factor.

2.1.2. Cumulative distribution function of source particles

The core source particles are sampled as follows: Firstly, cumulative distribution functions (CDFs) are calculated by 3D power distribution, fission nuclide fraction, fission spectrum, number of particles and energy released per fission. Secondly, source particle type, position and energy etc are calculated from CDFs.

The fission spectrum of mth assembly is:

$$\chi'(m,g',p) = \frac{\sum_{n=1}^{N'} f(m,n)\cdot\nu(n,p)\cdot\chi(n,g',p)\cdot T(g',p)}{\sum_{g=1}^{G(p)}\sum_{n=1}^{N'} f(m,n)\cdot\nu(n,p)\cdot\chi(n,g,p)\cdot T(g,p)} \tag{8}$$

Where m is assembly number, n is fission nuclide number, N' is number of fission nuclides, χ is fission spectrum of fission nuclide, χ' is fission spectrum of assembly, f is fission fraction of fission nuclide, ν is number of particles released per fission.

The energy CDF of mth assembly is calculated by summing up fission spectrum of assembly:

$$\overline{E}(m,g'',p) = \sum_{g'=1}^{g''} \frac{\chi'(m,g',p)}{\sum_{g=1}^{G(p)}\chi'(m,g,p)} = \sum_{g'=1}^{g''}\chi'(m,g',p), g'' = 1,...,G(p) \tag{9}$$

Where $\overline{E}$ is energy CDF.

The mesh source of particles is:

$$\hat{S}'(q,p) = \sum_{g=1}^{G(p)}\left\{\frac{C'\cdot P(q)\cdot B(q,p)}{K(m)}\sum_{n=1}^{N'} f(m,n)\cdot\nu(n,p)\cdot\chi(n,g,p)\cdot T(g,p)\right\} \tag{10}$$

Where C' is unit transform factor, 6.24×10^{12}MeV/(s·W), P is relative pin power, K is energy released per fission, MeV, $\hat{S}'$ is biased forward source of mesh, particle/(cm^3·s).

The space CDF of source particles is calculated by summing up mesh source of particles:

$$\overline{D}(q'',p) = \sum_{q'=1}^{q''} \frac{\hat{S}'(q',p)\cdot V_s(q')}{\sum_{q=1}^{Q}\hat{S}'(q,p)\cdot V_s(q)}, q'' = 1,...,Q \tag{11}$$

Where $\overline{D}$ is space CDF.

Number of particles is:

$$N(p) = \sum_{q}\hat{S}'(q,p)\cdot V_s(q)\cdot R(p) \tag{12}$$

Where N is number of particles, particle/s.

The particle type CDF is calculated by summing up number of particles:

$$\overline{F}(p'') = \sum_{p'=1}^{p''}\frac{N(p')}{\sum_{p=1}^{P'} N(p)}, p'' = 1,...,P' \tag{13}$$

Where $\overline{F}$ is particle type CDF, P' is number of particle types.

2.1.3. Sample procedure of source particles

Considering the above dependent relation of variables, source particle type, space and energy are sampled one after another.

1) For particle type, select random number $\xi_p \in (0,1]$, determine index p which satisfies $\overline{F}_{p-1} < \xi_p \leqslant \overline{F}_p$.
2) For space, select random number $\xi_q \in (0,1]$, determine index q which satisfies $\overline{D}_{q-1,p} < \xi_q \leqslant \overline{D}_{q,p}$. Then particle coordinates are sampled uniformly on space mesh.
3) For energy, select random number $\xi_g \in (0,1]$, determine index g which satisfies $\overline{E}_{m,g-1,p} < \xi_g \leqslant \overline{E}_{m,g,p}$. Select random number $\xi_g' \in (0,1]$, calculate particle energy as follows:

$$E' = E_g^l + \xi_g'(E_g^h - E_g^l) \tag{14}$$

Where E' is particle energy, MeV, E_g^l and E_g^h are lower and upper boundary of group g, MeV.
4) Particle direction is sampled uniformly on angular mesh.