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# A Study on Efficiency Improvement of the Hybrid Monte Carlo/Deterministic Method for Global Transport Problems

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## 1. Introduction

Analysis of radiation fields in nuclear facilities such as the proton accelerator, the nuclear reactor, the research reactor, and the fusion reactor are essential for the integrity of these facilities, the safety of workers and civilians, and the protection of the environment. However, it is not easy to carry out the MC calculation in large and complex system like streaming problem, which required to long computational time and large memory. Over the past several decades, a lot of variance reduction techniques have been developed to relieve requirements in the MC calculation.

As one of most successful variance reduction techniques, the Hybrid Monte Carlo/Deterministic methods dramatically increase the efficiency of the MC calculation for radiation transport analysis. By using Hybrid Monte Carlo/Deterministic methods, it can be obtained the desired quantities within a reasonable computational time. It refers to the overall procedure including both the deterministic calculation for generating variance reduction parameters and the Monte Carlo calculation for particle transport analysis. And methodologies such as CADIS [1, 2, 3], FW-CADIS [4, 5, 6] of Hybrid Monte Carlo/Deterministic methods have been demonstrated by their authors for validations and verifications in most radiation transport problems.

However, it still has difficulty to obtain desired quantities with uniform statistical precision in global transport problems. Because it is assumed that a Monte Carlo particle contributes to only a single bin during the deterministic calculation for generating weight window parameter. Then, the more outside of mesh tallies, which used to score the multiple quantities in MCNP code [7], the statistical uncertainty is higher in the desired global quantities. Therefore, in this study we introduced the indicator factor modified from the existing methodologies and offered the guideline for analysis of radiation fields in global transport problems.

## 2. Methods and Results

In this section the background theory of the CADIS and FW-CADIS methodologies are reviewed. Then, the modified indicator factor from existing methodologies is introduced. Finally, results from using this proposal are compared through adding to module in ADVANTG code [8] in simple test problem.

### 2.1 Background Theory

The linear time-independent Boltzman transport equation for a non-multiplying system [9] can be expressed by

$$\boldsymbol{H}\psi = q \ in \ V$$

Where $\boldsymbol{H}$ is the transport operator, $\psi$ is the particle angular flux, $q$ is the particle source distribution. If the both $\psi$ and $\psi^+$ are "well-behaved" functions in certain system which satisfy the continuity boundary condition, adjoint transport equation can be derived by

$$\boldsymbol{H}^+\psi^+ = q^+ \ in \ V$$

Where $\boldsymbol{H}^+$ is the "adjoint" transport operator, $\psi^+$ is the "adjoint" function, $q^+$ is the "adjoint" source. The solution of "adjoint" transport equation, that is "adjoint" function, is orthogonal with solution of "forward transport equation. From a CADIS methodology, when the "adjoint" source equal to detector response, "adjoint" function has physical meaning of "particle importance" [10].

$$\psi^+(P_0) = \int G(P_0 \to P)\sigma_d(P)dP$$

By using the physical meaning of "adjoint" function, the response such as flux, dose, and reaction rate can be estimated at phase space of interest through the MC calculation.

$$R = \int \psi^+(P)q(P)dP = \int \psi^+(P)\hat{q}(P) \cdot \frac{q(P)}{\hat{q}(P)}dP$$

This equation means that once "adjoint" function is calculated, it does not need to recalculate if the source distribution changes in same system. Then, value of weight window parameter can be obtained from a zero variance solution [11], which minimizes the variance of variance of estimated desired quantity at phase space

$$w(P) = \frac{R}{\psi^+(P)}$$

And Cooper and Larsen suggest method [12] for radiation transport analysis to obtain uniform statistical uncertainty in global transport problems. Then, simple concept of this method given by

$$m(P) = \frac{\psi(P)}{\overline{w}(P)}$$

Where $m(\mathrm{P})$ is the particle density, $\psi(P)$ is the particle angular flux, $\overline{w}(P)$ is the center value of weight window parameter. This method is demonstrated by its authors that estimates have approximately uniform statistical uncertainty in the MC calculation. With a same purpose to Cooper and Larsen method, The FW-CADIS methodology suggests that an “adjoint” source be consisted of appropriately weighted contributions from all tallies of interest and its general form given by

$$q^{+}(\vec{r},E)=\frac{\sigma_{d,1}}{R_1}+\frac{\sigma_{d,2}}{R_1}+\cdots+\frac{\sigma_{d,N}}{R_1}$$

### *2.2 The Proposed Weighting Method*

With same framework to FW-CADIS methodology, the proposed weighting method is performed in using ADVANTG code. For this purpose, two Deterministic calculations are executed by DENOVO code [13] in ADVANTG code. One is to calculate the “forward” flux from solution of transport equation for weighting to the “adjoint” source. The other is to calculate “adjoint” flux from solution of adjoint transport equation for generating the weight window parameters. In the first step of the Deterministic calculation, the “adjoint” source weighted by inverse of response is given by

$$q^{+}(\vec{r},E)=\frac{f(\vec{r})\sigma(E)}{\int dE'\sigma(E')\phi(\vec{r},E)}$$

Where $f(\vec{r})$ is the indicator factor, $\phi(\vec{r},E)$ is the “forward” scalar flux. Scalar angular flux calculated from Deterministic calculation in DENOVO code is integrated over the angle in the sense that, it is spatially extended compared to Cooper and Larsen method. Also, it assumed that a particle contribute to a tally bins for scoring and there are infinite number of bins to adjust multiple quantities like mesh tally. Therefore, the statistical uncertainty of desired global quantities is approximate to spatially three-dimensional normal distribution in the whole domain of the mesh tallies. Then, the indicator factor is weighted to inverse of probability which is in that position. This strategy was implemented to the module in the ADVANTG code. To verify proposed method, simple test problem is modeled by Fig. 1. Each block has size of 10 cm x 10 cm 10 cm. Result of this simple test problem is compared by Fig. 2-3

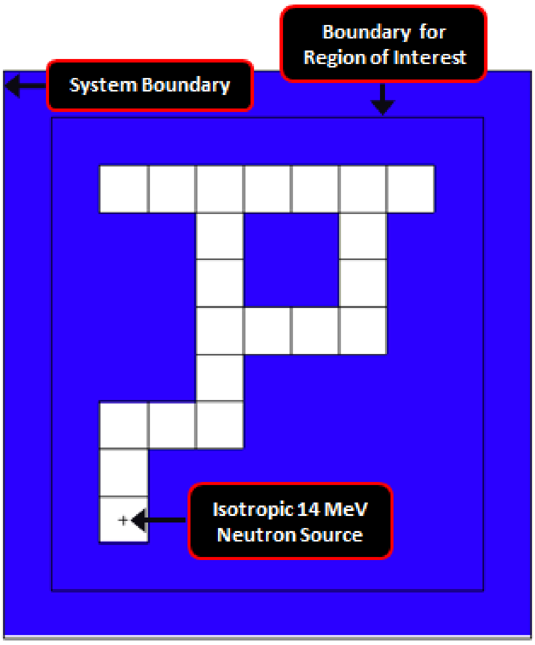

Fig. 1. Description of Simple Test Problem

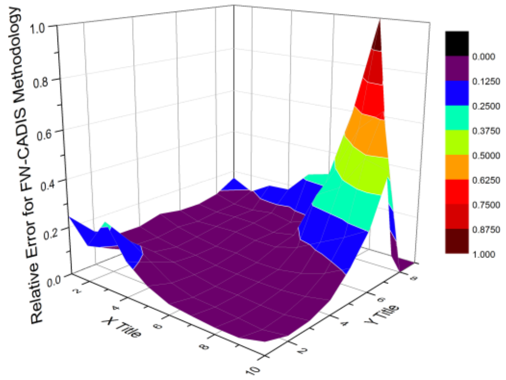

Fig. 2. Statistical Uncertainties for FW-CADIS

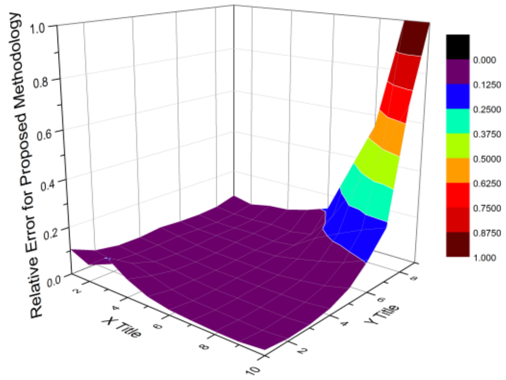

Fig. 3. Statistical Uncertainty for Proposed Weighting Method

## 3. Conclusion

In this study hybrid Monte Carlo/Deterministic method is explained for radiation transport analysis in global system. FW-CADIS methodology construct the weight window parameter and it useful at most global MC calculation. However, Due to the assumption that a particle is scored at a tally, less particles are transported to the periphery of mesh tallies. For compensation this space-dependency, we modified the module in the ADVANTG code to add the proposed method. We solved the simple test problem for comparing with result from FW-CADIS methodology, it was confirmed that a uniform statistical error was secured as intended. In the future, it will be added more practical problems. It might be useful to perform radiation transport analysis using the Hybrid Monte Carlo/Deterministic method in global transport problems.

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