Summary: Monte Carlo Variance Reduction for Multi-physics Analysis of Moving Systems

Chelsea A. D'Angelo

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The rapid design iteration process of complex nuclear systems has long been aided by computational simulation. Traditionally, these simulations involve radiation transport in static geometries. However, in certain scenarios, it is desirable to investigate dynamic systems and the effects caused by the motion of one or more components. For example, fusion energy systems (FES) are purposefully designed with modular components that can be moved in and out of a facility after shutdown for maintenance purposes. It is particularly important to accurately quantify the shutdown dose rate (SDR) during maintenance procedures that may cause facility personnel to be in closer proximity to activated equipment. The SDR is caused by the photons emitted by structural materials activated by neutron irradiation during device operation. This type of analysis requires neutron transport to determine the neutron flux, activation analysis to determine the isotopic inventory, and finally a photon transport calculation to determine the SDR.

While Monte Carlo (MC) calculations are considered to be the most accurate method for simulating radiation transport, the computational expense of obtaining results with low error in systems with heavy shielding can be prohibitive. However, variance reduction (VR) methods can be used to increase the computational efficiency. There are several types of VR methods, but the basic theory is to artificially increase the simulation of events that will contribute to the quantity of interest such as flux or dose rate.

One class of VR techniques, known as hybrid deterministic/MC, takes advantage of the speed of deterministic codes to calculate an estimate of the adjoint flux to automatically generate biasing parameters to accelerate MC transport. The adjoint flux has significance as the importance of a region of phase space to the objective function.

One hybrid VR technique used to optimize the initial transport step of a coupled, multi-step process is known as the Multi-Step Consistent Adjoint Driven Importance Sampling (MS-CADIS). The basis of MS-CADIS is that the importance (adjoint) function used in each step of the problem must represent the importance of the particles to the final objective function. In the specific case of SDR calculations, the importance function for the neutron transport step must capture the probability of materials to become activated and subsequently emit photons that will make a significant contribution to the SDR.

The Groupwise Transmutation (GT)-CADIS method is an implementation of MS-CADIS that optimizes the neutron transport step of SDR calculations. GT-CADIS generates an adjoint neutron source based on certain assumptions and approximations about the transmutation network. This source is used for adjoint neutron transport and the resulting flux is used to generate the biasing parameters to optimize the forward neutron transport.

For cases involving geometry movement after the initial radiation transport, such as SDR calculations during maintenance activities, the importance of the moving regions to the objective function changes over time. The necessitates a construction of the adjoint neutron source that takes the movement into account. A new hybrid VR technique that extends GT-CADIS for dynamic systems by calculating a time-integrated adjoint neutron source is currently in development. This method is called the Time-integrated (T)GT-CADIS method and to date, tools have been developed to implement rigid-body transformations on CAD-based geometry and to collect and manipulate the adjoint flux data from each time step of geometry movement after shutdown.

The successful completion of this project will demonstrate the efficacy of a workflow and tools necessary to efficiently calculate quantities of interest resulting from coupled, multi-physics processes in dynamic systems. The specific case demonstrated will be the comparison of efficiency in analog versus TGT-CADIS optimized quantification of the SDR in an experimental or conceptual model of a fusion energy system.