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Bi-level spatial subdivision based monte carlo ray tracing directly using CAD models

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ABSTRACT

To achieve fast Monte Carlo ray tracing on CAD models, a Bi-level Spatial Subdivision based ray tracing method (BSS) is proposed in this paper. This method was implemented and integrated in Super Monte Carlo Program for Nuclear and Radiation Simulation (SuperMC) and tested on ITER Benchmark and Force-Free Helical Reactor (FFHR) model. The testing results on ITER Benchmark model demonstrate the correctness of this method. The testing results on FFHR demonstrate that this method can save most of the preprocessing work to greatly improve the Monte Carlo analysis efficiency. Both results reveal that this method achieves applicable calculation speed comparing to the traditional Constructive Solid Geometry (CSG) broadly used in Monte Carlo codes.

1. Introduction

Monte Carlo (MC) method has been well applied to Fusion Neutronics analysis for it's convenient to describe complicated geometry [1]. To achieve fast Monte Carlo geometry modeling, geometry modeling methods based on CAD have been developed [7,14,15,21]. Using the CAD based method, great advances have been introduced, and promoted the development of fusion neutronics.

There are two major kinds of CAD based geometry modeling methods, the CAD to CSG conversion [7,13,16] and the direct CAD based ray tracing [4,6].

As revealed, the CAD to CSG conversion method is time consuming. CSG geometry cannot describe arbitrary solids, such as solids with twisted or curved high order surfaces that often used in CAD models. The CAD to CSG conversion relies on Boolean operations provided by CAD systems (such as ACIS and OpenCasCade), which is not stable to handle solids with intricate surfaces. Furthermore, time consuming preprocessing is needed to remove including those above before converting CAD solids to CSG description.

Currently, several works for direct ray tracing directly on CAD geometry have been implemented. MCNP6 adopts unstructured mesh [3] which can directly be generated from CAD models. Geant4 itself integrated a 2D mesh based ray tracing function [5]. The direct CAD based ray tracing is slow in computing speed. As a result, there's still space for these methods to be improved to achieve convenient application in Monte Carlo calculation. For example, the DAGMC adopts Oriented Bounding Box (OBB) to accelerate the ray tracing on 2D mesh [4], Geant4 redefines complex closed tessellated surfaces as tetrahedral meshes to accelerate the navigation process in Geant4 [5].

In order to achieve high calculation efficiency in geometry calculation, several methods have been developed in SuperMC, such as Optimal Spatial Subdivision (OSS) [22,12]. But it is designed for CSG based geometry, in which each solid is described by limited elements. It is not able to further accelerate the raytracing in a single solid that contains abundant geometry elements, such as facet based geometry, in which each solid is described by an enormous number of faces. This paper proposed a Bi-level Spatial Subdivision (BSS) based Monte Carlo ray tracing method directly on facet based CAD models for particle transport simulation and implemented it on Super Monte Carlo Program for Nuclear and Radiation Simulation (SuperMC) [8], which is a general, intelligent, accurate and precise simulation software system for the nuclear design and safety evaluation of nuclear systems [2,9,10,11,17–20].

2. Methodology

2.1. Generation of facet geometry

CAD models describe the accurate geometry of a solid. It forms solids with a topology structure consisting of face, edge and vertex, in

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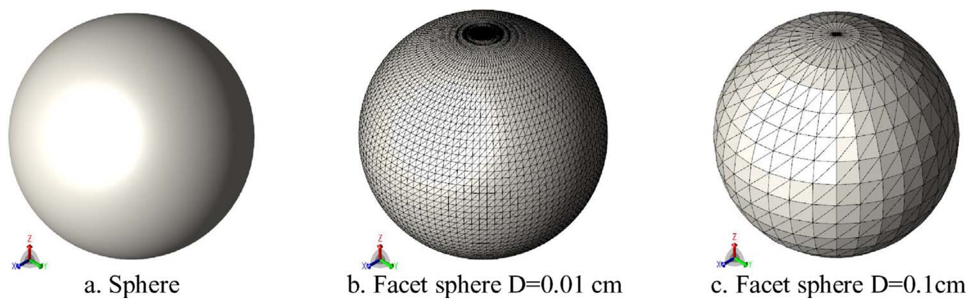

Fig. 1. Facet geometry with different Ds of a sphere with 10 cm radius.

which the face stands for the exact boundary shape of the solid.

A facet is a triangle associated to a direction parallel to its normal and to the outside of the solid. Facet based geometry describes solids using combined facets, where each edge of the facets connects two adjacent facets. Fig. 1 shows a sphere and corresponding sphere faceted in two different maximum deviations (referred to as parameter D in this paper), in which the maximum deviation means the maximum distance between the facets from the original solid boundary. As demonstrated in the figures, smaller deviation standing for higher accuracy, leads to more facets. A Bi-level Spatial Subdivision method which is described in Section 2.2 was proposed to accelerate the calculation with the large amount of facets.

On the basis of facet techniques supplied by the existing CAD engines, a facet based MC model generation procedure has been implemented in SuperMC. It stores the whole model in two files. One contains all the model setup information including IDs associated with the facet solids, material, tally, source and other calculation parameters; the other contains all the facet solids.

2.2. Bi-level spatial subdivision

In order to achieve efficient calculation on geometry with large amount of basic elements, the key point is to limit the number of basic elements in the ray tracing progress.

The ray-tracing method named BSS is based on two levels of spatial subdivision (Fig. 2): The solid level spatial subdivision divides the whole transport space into hierarchical tree, in which every leaf node contains a limited amount of solids, to make the solids involved in a single ray tracing step few. The facet level spatial subdivision divides the bounding box of each solid into a facet level spatial subdivision tree, in which every leaf node contains a limited number of facets, to restrict the amount of facets involved in a single ray-tracing step small. Both levels adopt BSP (binary space partition) method, which is widely used in computer graphic domain [23].

2.3. Ray tracing with BSS based facet model

For the particle transport, two key functions of the ray tracing module with geometry model are: 1. the function to search for a solid containing a given point, 2. the function to predict the distance of the point on the boundary of the current solid where the current particle is about to exit through or the point on the boundary of the next solid current particle is about to enter through.

To search for a solid containing a given point, the point is firstly located layer by layer to a leaf node in the solid level space subdivision tree. For each solid in the sub region, a ray starting from this point with arbitrary direction is tested, if the first facet intersect with the ray is with forward direction as the ray (the dot product of the direction of the ray and the facet is larger than 0), the point is then determined as inside the solid. If no such solid is found, the point is determined as outside of all the solids.

To predict the distance of a given point to the boundary in a given direction, if the point is inside a solid, the nearest facet with forward direction as the given direction would be found and the distance is calculated. Otherwise, the first intersecting facet to the ray starting from the point and the given direction with backward direction (the dot product of the direction of the ray and the facet is less than 0) in the sub regions is identified. The distance between the point and intersection point is obtained as the prediction.

Two functions all depend on locating the first intersecting facet to a ray. This facet is obtained through following steps. 1. The first intersection point to the sub regions is calculated layer by layer on the solid tree, until the leaf sub region. 2. Each facet in the sub region is tested with this ray for all the intersecting facets. If no facet in the sub region intersects with the given ray, the adjacent sub region intersect with the ray will be tested with the same steps.

3. Testing of BSS method

3.1. Testing on ITER benchmark model

To verify the correctness of BSS, ITER Benchmark model was adopted as the test case. In the previous work, SuperMC has been verified on the CSG model of ITER Benchmark, this work takes this CSG model as baseline (Fig. 3).

ITER Benchmark model was built by ITER International Organization to verify the CAD based modeling software, such as SuperMC/MCAM, McCad in 2006. It contains the main parts of the ITER tokamak machine, including blanket, divertor, vacuum vessel, cryostat, bioshield, central solenoid coils, TF coils, PFcoils, lower, upper, equatorial ports and et al.

3.1.1. The analysis of the parameters in BSS method affecting the ray tracing speed

Two key parameters in BSS method directly determine the transport calculation speed and the accuracy. They are shown as follows.

1. Min Facet Number in facet grids (MFN): During generating the second level tree for a facet solid, the parameter of min facet number in facet grids.
2. Deviation (D): The maximum deviation (in another word, the maximum distance) between the faceted surfaces and the original surfaces.

As the parameters can only influent the ray-tracing on geometry, several calculations on the model with void material were performed on the same computer. Multiple sets of parameters were tested on the viewpoint of both efficiency and accuracy. In each calculation, 10,000,000 histories were simulated, the source was the plasma source released with ITER Benchmark, and it was configured as with no reflecting surface or material.

To choose the valid D for faceting the models, comparison of the flux calculation results of all the void solids were compared. Fig. 4 compares the results of the flux calculation between two typical D parameters. The calculation results on CSG model were taken as the baseline. As the figure shows, the deviation increases linearly with the