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The Large-Scale Auto Modeling Tool for Monte Carlo Simulations

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Abstract

The DAYAWAN reactor core pin-by-pin model has complex geometry, it contains 157 fuel assemblies, and each fuel assembly contains 17*17 fuel pins. In order to achieve a precise power distribution of the core by MC calculation, each of the fuel pins should be at least divided into 16 axial sections, then the number of the pins is 725968, hence the total solid number of the reactor may be over millions. In order to efficiently generate complex models such as DAYAWAN, it is necessary to develop visual modeling tools based on CAD kernel. Therefore, we developed the JLAMT software. By using this tool, the DAYAWAN pin-by-pin model was created easily.

Keywords: Field Oriented Modeling, Pin-by-Pin, Hierarchical Geometry Tree, GDML

1. Introduction

The Monte Carlo (MC) transport calculation method is widely used in nuclear design and assessment, especially in neutronics analysis such as reactor core design, reactor shielding design and reactor safety analysis. It simulates large amount of neutrons' transport histories in different mediums. It is necessary to give a geometry description of mediums. With the numerical and engineering simulation progressing, results with high confidence can be achieved by using high performance scientific and engineering computing applications. In order to achieve results with high precision by MC calculation, much more detailed geometry of model should be given[1]. Take the DAYAWAN reactor core as an example, the core consists of 157 fuel assemblies, each assembly has 17*17 fuel pins, and in order to get a precise power distribution of the core, each pin should be divided into 16 sections. Then the total solid number of this model reaches 725968.

In order to simulate reactor pin-by-pin model such as DAYAWAN, the Institute of Applied Physics and Computational Mathematics (IAPCM) developed a neutron-photon coupled MC code JMCT (J Monte Carlo Transport), based on the CERN's MC program Geant4[2]. Although Geant4 supply a complete geometric description capacity, it lacks a geometric modeling tool. Users should build models by manually writing text files. A simple model can be easily built by this method, but many problems will arise when dealing models with complex geometries: 1) Modeling efficiency is low and building complex models costs too much time. 2) Complex Boolean operations are hard to realize. 3) Error checking is hard in complex models. 4) Modifying subtle error is trivial and fallible. As MC algorithm develops, the manual modeling method becomes a restriction. In order to handle models with complex geometry such as the DAYAWAN pin-by-pin reactor core, we developed a modeling tool JLAMT (J Large-scale Automatic Modeling Tool).

2. The visual modeling tool JLAMT based on field oriented development

In order to improve 3D modeling efficiency, it is necessary to develop a visualized modeling tool based on CAD kernel. UG is one of the most advanced CAD, CAM software. Therefore we did the secondary development on UG which forms JLAMT. JLAMT will automatically export GDML (Geometry Description Markup Language) type files which can be used by GEANT4, JMCT and other MC codes.

There are two main methods to store 3D models, the CSG and the BREP. The basic idea of the CSG method is: any arbitrary 3D models can be achieved by using series of complex Boolean operations between simple voxel. The CSG method can be regarded as an ordered binary tree. The leaf nodes are basic voxels, the intermediate nodes are Boolean solids, and the root node is 3D model. The main advantage of CSG method is that its data structure is simple, the memory consume is small, and the memory management is easy. Many MC codes choose CSG as their geometry description method, including Geant4 and JMCT.

In general, a CAD system uses the Boundary representation (BREP) to define solids. BREP solids are defined via the description of their boundaries; it contains detailed data of geometry (shape) and topology (how things are connected). Furthermore, commercial CAD software usually uses special file format for data exchange. Because of difference in the representation schemes and file format, the needs for conversion make necessary. Today, the study is concerned with the conversion of geometric representation. However, the algorithms is reliable that solid model is transferred from CSG to BREP; in contrast, it is very difficult to transfer BREP to CSG, no further result can be found with the technique.

All modern CAD systems are based on the feature based design paradigm, also called parametric design and history based design. Feature based model is represented as a graph(or tree or list) of operations called features[5]. The tree is sometimes called the ‘history tree’. Operations create new geometry or modify existing geometry. Feature based design is basically an extension of constructive solid geometry (CSG). In the result, the complex model can be described as :

Model = {feature1 operation1 feature2 operation2…… featuren operationn}

The differences are that in feature based design there are more operation types. So if the feature type is restricted within the GDML limits, then it is possible to successfully exchange feature tree to GDML geometry tree.

Unfortunately, there are great differences between the CAD model and the physical model used by MC code. The data structure to store geometry is completely different. Not only the geometry, but only the materials and other neutronic parameters are also needed. Also, MC codes do not allow overlap between solids. Therefore, it is necessary to do conversions between these types.

The feature model not only provides the geometry data, but also provides the set of operations dependent upon all proceeding feature. Five steps are performed in auto-modeling tool to convert the CAD model to neutronics model: 1) accessing CAD feature tree, 2) feature recognition, 3) feature extraction, 4) translation it, since the definitions of same shape may be different, their spatial position, the coordinate system are not equated with the MC codes, the conversion algorithm is performed; 5)create the GDML geometry tree and export it.

The flow diagram for auto-modeling tool is shown in figure 1.

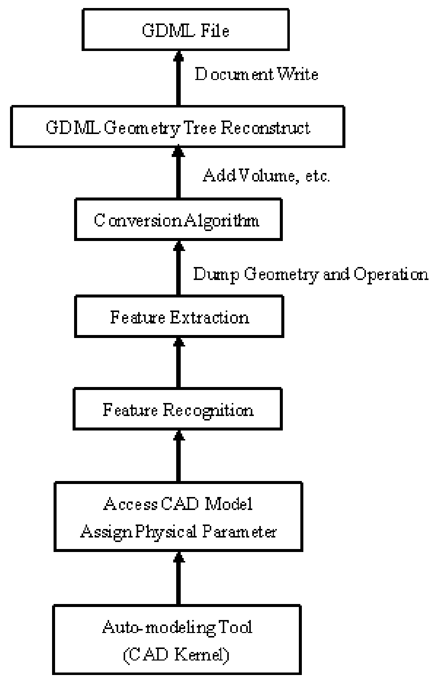

Figure 1 The flow diagram of the auto-modeling tool

Lots of MC modeling programs are designed and developed mainly focusing on the conversion algorithm, but special modeling needs are neglected. It is still very difficult to build a complex device model even if using CAD software. Our goal has been to provide the interactive interface to quickly manipulate model, assign and modify the physics properties associated with the model, JLAMT designed some fast modelling modules for special voxels. The UI and voxles is shown in Figure 2.

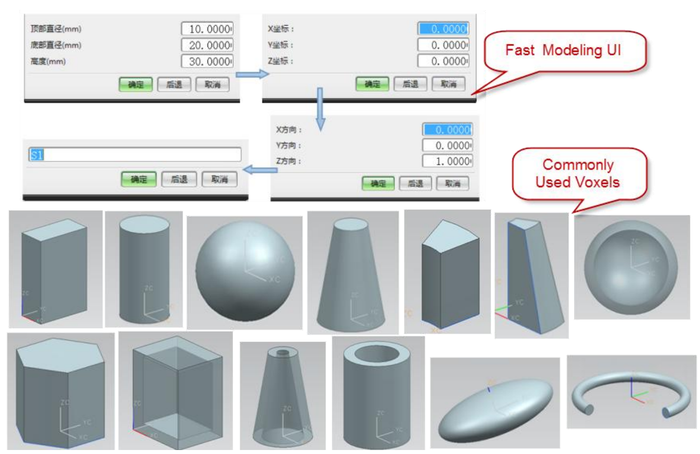

Figure 2 The fast modeling tool of JLAMT

It is a fact that although a reactor core is complex, it has a lot of repeated structures. Based on this field special knowledge and needs, we developed modules aiming at fast reactor core modeling on JLAMT. It uses parameterized methods to simplify the reactor assembly modeling procedure. The assembly modeling UI is shown in Figure 3.

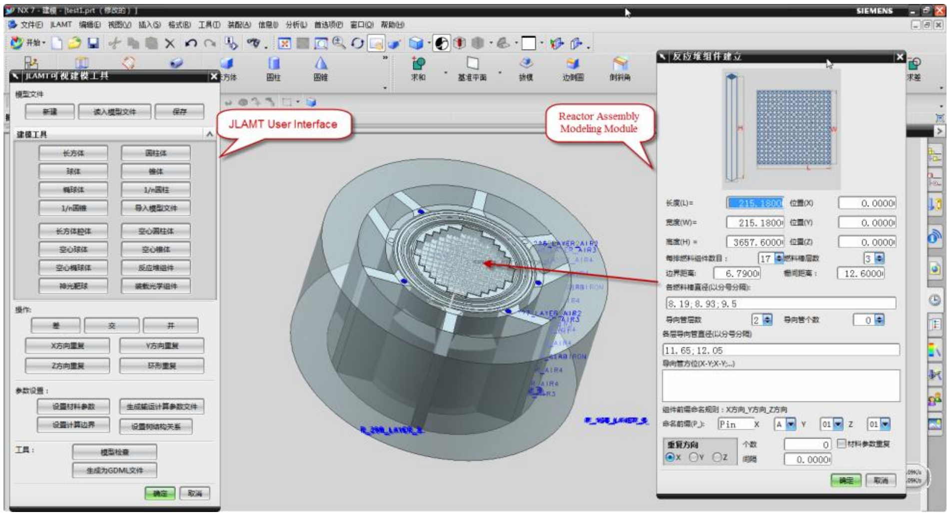

Figure 3 The reactor assembly modeling tool of JLAMT

We developed JLAMT mainly focusing on MC code users' special needs and habits of geometry and physical modeling. The program supplies a guided interface, which makes the user to set parameters (such as solid type, location, direction, name, material, neutronics parameters and so on) step by step. The user may build MC models without trainings by using JLAMT.

3. Geometry description method of GEANT4 and JLAMT code

In CSG method, a physical model is often formed by different types and size of solids. To define a complete physical model, the types of solids, the relative position and location between them, and the materials and neutronics parameters should be given completely. A complete description of a physical in Geant4 should use three layers definition[3]:

1. Solids. Define the type and size of objects.
2. Logical Volume. Define the materials of solids.
3. Physical Volume. Define the positions and rotations of logical volumes.

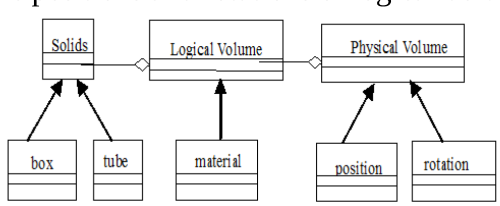

Figure 4 Three layers definition in Geant4

The three layers definition makes Geant4 a flexible ability in geometry description. Solid layer defines the basic geometry information. Solids with same shape but different materials can be repeated by using Logical Volume layer. Logical Volumes with same geometry and material but different placements can be repeated by using Physical Volume layer[4]. By using three layers definition, it's much easy to describe repeated structure, and it's much efficient and clear to build and manage large-scale models.

In CSG method, different types of solid determine the geometry description ability. Geant4 supplies not only some basic voxels (such as box, sphere, cylinder, cone, etc.), but also some special voxels (such as ellipsoid, torus, twisted box, etc.). Based on these voxels, complex Boolean operation can be done.

These guarantee Geant4's ability of building complex geometry. All types of voxels and Boolean operations are supported by JMCT.

Another method Geant4 use to describe geometry is the mother-daughter relationship between solids. This property mainly describes the inclusion relations between two volumes. Fig.5 is an example: volume "a" contains volume "b", "c", "d", then volume "a" is the mother volume and volume "b", "c", "d" are the daughter volumes. The daughter volume such as "c" can also have its daughter. Though the number of hierarchy levels is not limited, there must be only one root volume "world". These volumes form a hierarchy geometry tree. This method greatly simplifies the description of repeated structure. Take Fig.5 as an example, if one needs to describe another volume "a1", which has same geometry with "a", he should describe branch "world-a-c-e" in detail, and then repeat "a" once as "a1", he needs not to describe "world-a1-c1-e1" branch in detail because volumes inside "a1" (such as "c1", "e1", etc.) are implicitly repeated. In DAYAWAN reactor core model, geometry is same among assemblies, by using mother-daughter relationship, repeated structure modeling work can be greatly reduced. Also, the MC transport calculation does not need to simulate in global geometry, but to simulate in geometry branch. Computing time can be greatly reduced.

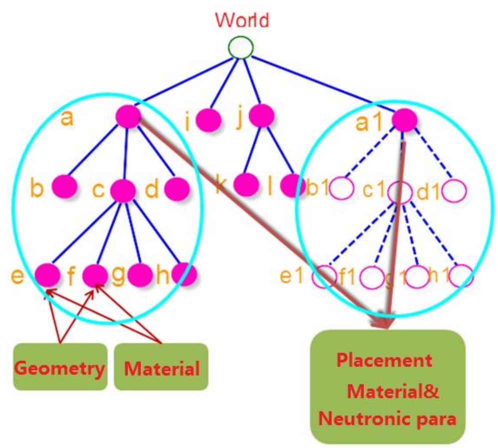

Figure 5 Sketch map of hierarchy geometry tree

JLAMT works as a pre-processing unit for JMCT. It converts feature data in UG to CSG data based on GDML, which can be read by JMCT. In order to arrange data properly, we developed data structure which is consistent with GEANT4 to represent the large-scale models. Because of the different of its geometrical definition, JLAMT implements the algorithm to complete the transformation. JLAMT can now handle several voxels such as box, sphere, cylinder, cone, torus, hexagonal prisms, etc. Any arbitrary hierarchy trees can be set by users. Any placement and rotation as well as complex Boolean operations can be converted.

One would face a series of problems if he builds a large-scale complex model on PC. The memory may be insufficient, and the interactive or display speed may be unbearable. Therefore, we developed a new method, "implicit modeling" based on hierarchy geometry tree description. Take the DAYAWAN reactor core as an example, shown in Fig.5, the core consists of 157 fuel assemblies, and each assembly has 17X17 fuel pins, and each pin has three layers; Each assembly is divided in 16 assembly block axially. So in the core there are 2512 assembly blocks, and each block contains the same 17x17 pin structure. The total solids number is 2177904, which is too large to model and display in UG. If we use implicit modeling, we only need to build 17x17 pin structure in one block in detail, for the other 2511 blocks, we only build simple boxes without detailed geometry in them. In JLAMT, we label these 2511 repeated blocks and make them reference to the detailed one. In the final converted GDML, 17x17 pin structure in each block is implicitly repeated, while in the CAD model only one block's detailed geometry is displayed. The implicit modeling can be explained by Fig.5, volume "world" can be regarded as core, volume "a" is one assembly block, volume "b", "c", "d" are fuel pins, and volume "e", "f" are layers in each pin. This branch is a geometry subtree which contains complete 17x17 pin structure geometry information. The other 2511 blocks are volume "a1", "a2"… which have same geometry as volume "a". They can be built by only repeating the root node of a subtree, and the geometry information inside is implicitly repeated. By using this method in JLAMT, we guarantee that models with millions of repeated solids can be displayed by thousands of solids in CAD, and large-scale models with amounts of placement data and complex mother-daughter relationship such as DAYAWAN core model can be converted to GDML correctly.

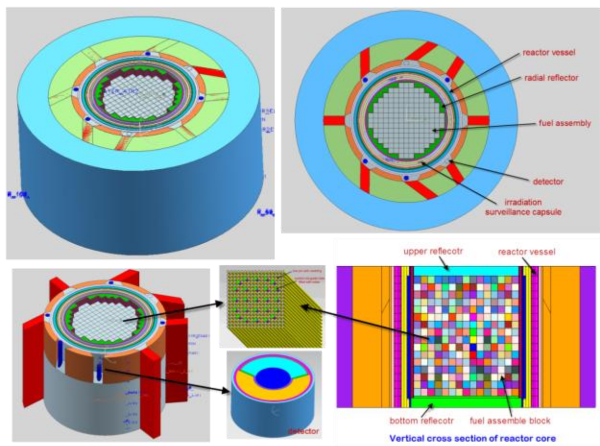

Figure 6 The rendering picture of DAYAWAN reactor full-core

4. Geometry description file format GDML

A GDML file consists of five parts[6]:

1. <define>…</define>: It defines constants, placement parameters (location, rotation). This part can be referenced by latter part of the file.
2. <material>…</materials>: It defines the kind of mixture filled in solids.
3. <solids>…</solids>: It defines solids types, including 24 kinds of basic voxel and their sizes. It also defines solids built by complex Boolean operations (intersection, union, subtraction).
4. <structure>…</structure>: It defines logical volumes and physical volumes, and how hierarchy geometry is organized by these volumes. It also defines the materials of logical volumes, and the placements of physical volumes.
5. <setup>…</setup> : It defines world, the root of all geometry subtrees.

These five parts are relatively independent. Data in different parts can refer to each other. The same constants, materials parameters, and hierarchy trees need only to be described once, and they can be referenced many times as repeating. GDML files are suitable to describe large-scale model.

Users can build models by using JLAMT's or UG's interaction functions. JLAMT can automatically convert CAD models to GDML files for users to do further transport calculations.

5. Conclusions

We introduce the modeling tool JLAMT specially designed for MC transport geometry modeling. It is developed based on feature modeling technology of CAD. The field based development tool JLAMT supplies faster and more convenient operations than manually modeling, which shortens the user's learning cycle. Based on UG, JLAMT supplies a friendly user interface, which makes the user easy to build, edit, and modify geometry. It also supplies multiple ways for users to set materials and other physical parameters, which makes the user efficient to build physical models. JLAMT can automatically convert large-scale models with complex geometry in CAD to GDML file, the hierarchy is used as a natural way and as an efficient way of organizing the geometry, which can be used by CSG based MC transport program to do further calculation.

The DAYAWAN reaction model is transferred to calculation model by JLAMT. Figure 7 gives the simulation results of JMCT code. The results are good; this also means the auto-modeling tool is a feasible and effective way for MC model input.

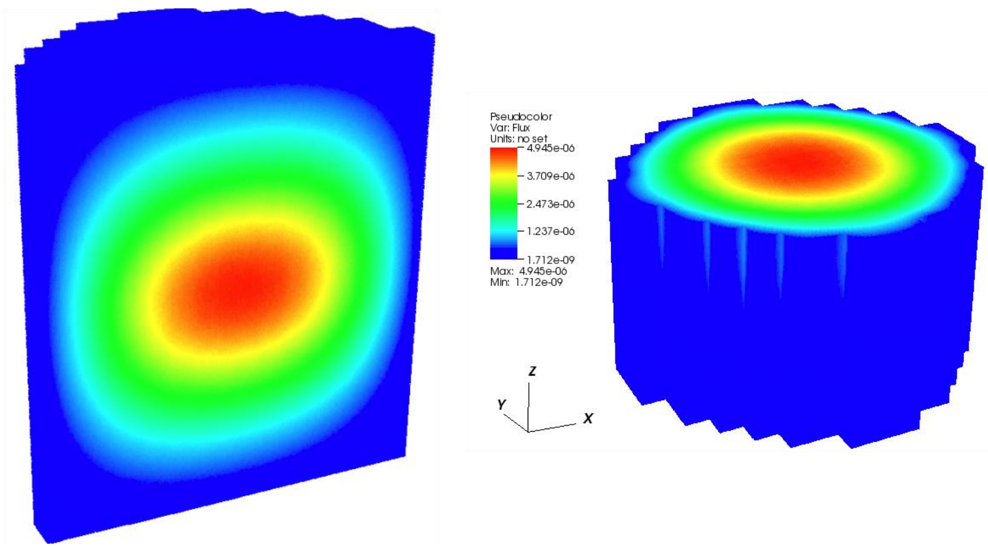

Figure 7 Total Flux figures of all fuel cells

6. Acknowledgments

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