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Virtual plasma chamber integrated multi-physics simulation: Status and next steps

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ABSTRACT

A modest approach to develop the ISPC enabling tool for fusion plasma chamber systems has been achieved. This high performance computing simulation addresses 3D physical phenomena in a complex and heterogeneous virtual fusion plasma chamber system and opens a new way for how one, such as DEMO/FNSF, ought to be designed and modeled. In the current approach, complex FNST scenarios were simulated and modeled through a community-built reflective middleware for simulation integrations involving multiple simulators. Example advancements are presented while issues and ideas are discussed to further expand the development of such a tool.

1. Introduction

Over the past five years, ITER has provided the framework for the development of an advanced computing, integrated simulation predictive capability (ISPC) for tokamak fusion plasma chamber components. This high performance computing simulation addresses 3D physical phenomena in a complex and heterogeneous virtual fusion plasma chamber system and opens a new way for how one, such as DEMO/FNSF, ought to be designed and modeled. Primarily, the ISPC models physical phenomena using 3D CAD models representing actual device components, at a high level of fidelity thereby substantially reducing design risk and cost. The physical scenarios involve multiple interacting scientific disciplines and require a diverse set of simulators/solvers to better interpret the real world phenomena. In current practice, the analysis suite consists of various codes solving for neutronics, transient electromagnetics (EM), CFD/thermofluid, magneto-hydrodynamics (MHD), tritium transport, pebble bed thermomechanics, and structural stress analysis as shown in Fig. 1 [1]. Translation routines/scripts were developed to pass output from code to code, where different geometry representation and simulation data formats are used. Translation between the solvers is less desirable, and while a multiphysics code which allows the use of the same mesh in each solver and permits the solution fields to be easily interchanged between the solvers is more favorable, such is often not the case. Individual physical modeling codes are developed by domain experts and have varied computational needs. The domain experts who may have an in-depth understanding of one particular phenomenon being modeled are typically evaluating and executing that knowledge separately. The development of a single multi-physics code for fusion nuclear science and technology (FNST) seems to be outside the scope of current development efforts. Facilitating the process by pulling independently created models together into an interoperating multi-simulation model may still be the mechanism to develop FNST ISPC.

The challenge is not only in the area of translating data between the codes, but also, from the simulation perspective, in simplifying the geometric details of many unique features involved in the design that meet the functional requirements. For example, in the ITER enhanced heat flux first wall design, there is a need to include hypervapotron teeth in the CFD/thermo-fluid analysis; however, if they are included in transient EM analysis it would make the mesh unnecessarily large. The questions of which simplifications to use in one simulation code and how to extrapolate the

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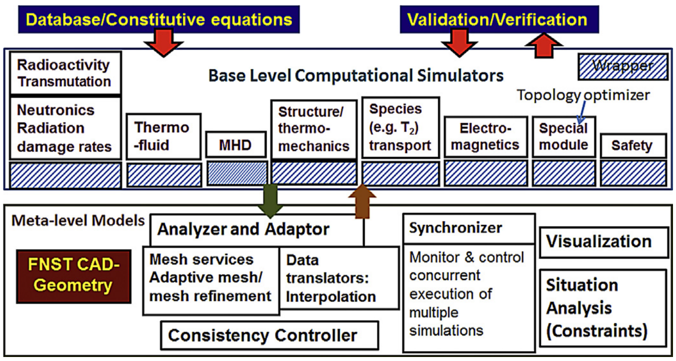

Fig. 1. Integrated simulation predictive capability (ISPC) framework.

information to other codes in the regions where simplifications should be made are more relevant. Here again the domain knowledge plays a key role in building the integrated simulation tool. The advantage of building an integrated simulation environment remains tremendous, bringing the design closer to a success: an envisioned virtual plasma chamber systems package that can be instrumental in providing information not easily obtainable through multi-effect physical experiments.

Much progress relevant to the ISPC development has been made in ITER neutronics, ITER FW/shield blanket module design exploration and analysis, and ITER TBM design and analysis. In this paper, examples of progress in these areas are presented, while issues and ideas are discussed at the same time to further expand the development of such a tool. These issues and ideas address the simulation integration environment, time synchronization (time sync), simulation simplification, the use of the optimization tools and visualization.

2. Simulation integration environment

The development of simulation integration for a fusion plasma chamber system is a challenging feat but can benefit from comparison to similar integrations in other fields. Simulation integration has been studied extensively in the defense and gaming industries, in particular that common frameworks and or standard architectures for simulation integrations have been developed by the US Department of Defense [2]. There is no such similar support to develop a common framework for the development of an integrated simulation platform for FNST. The FNST and the U.S. ITER FW/shield blanket design team effort in developing this integration architecture more closely resembles the growth of reflective middleware architecture [2,3].

The middleware architecture alleviates flexibility impediments that arise when combining pre-existing simulators. This is achieved by removing the need to conform the internal properties of the simulators. In the middleware architecture, integration of different simulators is achieved by using the meta-level for specifying/modeling the properties of the different simulators and reasoning about the interactions among the different simulators. The meta-level is structured as a series of meta-models representing the various simulators, where actions, data, input or output parameters, constraints, etc. are extracted. Simulators are interfaced with meta-level by using a wrapper. The wrapper communicates with simulators and sends the information and interdependent data item to the meta-level. Upon receiving such actions from a simulator, the metal-level generates meta-actions to notify any dependent simulators. Although meta-level development is more in the field of computer science, its accuracy of execution relies on knowledge of the underlying physics of the domain.

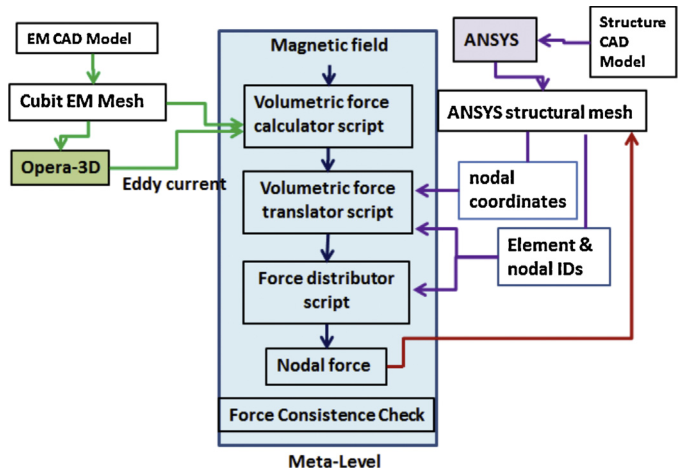

Fig. 2. Example wrapper and meta-level models for integrated EM and structural simulations using Opera-3D and ANSYS simulators.

As an example, the application of middleware architecture for a previously proposed FNST integrated simulation platform is illustrated in Fig. 2 [1,4,5]. The wrapper from an EM simulator consists of EM mesh and nodal information, centroid of element, and the calculated elemental eddy-current distribution. The wrapper also contains information from the structural simulator, the information consists of structural element information, the centroid of the element, and the coordinates of the nodes. The wrapper communicates with both simulators and then passes them both to a meta-level model which includes many analysis scripts to derive volumetric forces, transfer these forces to structural mesh nodes, and ensure force conservation during the data transfer. The nodal EM forces to the structural analysis were derived in a two-step process. First the eddy-current distribution calculated using the Opera-3D software [6] was coupled with the magnetic fields of the device to calculate the elemental volumetric force for EM mesh. Then the volumetric forces were transferred to nodal forces of the structural elements for stress analysis. The ANSYS [7] wrapper sent the information of the nodes associated with the element meshes for the stress analysis and node coordinates, while it received nodal force data for the stress analysis. The meta-level model created a table file for the locations of the element centroids for ANSYS meshes, imported this file to the Opera post-processor and extracted the EM forces at element centroids from EM analysis. The element force data is distributed among the nodes associated with the element to give the loads for the stress analysis. Lastly, the correctness in force transfer is checked.

A further question arises in whether the structural deformation caused by the EM forces would impact the current flow during the disruption event, in which time sync is needed to determine how simulation and interaction between the two simulators should be conducted. In the research area of time sync, the time sync mechanisms can fall into two different categories: conservative or optimistic [8]. A conservative strategy ensures the legality of simulator actions by delaying the actions such that the dependencies are preserved in the concurrent execution of actions or different simulators. In the optimistic strategy, the violations are accepted first, but instead of trying to prevent them by delaying the actions, we simply choose to detect them after the action has executed and then resolve the violation when it does occur; by aborting the actions that caused the violation. The details of time sync research are beyond the scope of the current activity. A case study is performed to examine time-dependent interactions between structural deformation evolution during plasma disruption (MD_UP_LIN) event and the resulting EM loads. The peak load imposed to blanket module