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A Generalized Method for One-Way Coupling of CTH and Lagrangian Finite Element Codes with Complex Structures using the Interdisciplinary Computing Environment

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Abstract

In the past, CTH (a finite volume, shock physics code) has been coupled with different Lagrangian finite element codes like Pronto3D and LS-Dyna, to solve blast-structure interaction problems. In many situations, a two-way coupling of these codes is unnecessary. Specifically, when the deformation of the structure has little impact on the developing blast, a one-way coupling is sufficient. Unfortunately, when the structure is complex, and particularly when the model contains shell elements, accurately generating the load curves for the finite element input can be difficult.

A generalized method for generating the necessary load curves for the finite element input from CTH has been developed at ARL by using the Interdisciplinary Computing Environment (ICE). While others have successfully coupled CTH with finite element codes in the past, this method accurately represents the finite elements model's geometry on the Eulerian mesh and can be applied to any code with a pressure vs. time element loading capacity. An accurate representation of the finite element model is inserted into the CTH mesh even if the model contains shell elements. Using this method, an example problem of a land mine interacting with a complex vehicle structure is presented.

Multi-disciplinary weapon-target interaction problems (from first principles) require solutions of complex and very large-scale equations and the use of parallel computers. Examples such as blast-structure interactions and projectile-buried structure interactions require software from different disciplines to be coupled in order to provide a complete understanding of the detailed interaction.

A large class of these computational problems do not neatly fit into a pure Eulerian or pure Lagrangian approach. Arienti et al.[1] point out that Eulerian approaches are excellent at allowing for the development of a complex flow at the price of loss in accuracy when tracking a boundary. Lagrangian approaches intrinsically track the boundary, but lose accuracy when the mesh becomes highly distorted. Hybrid methods such as "Arbitrary Lagrangian Eulerian" (ALE), attempt to combine the two methods, but suffers it's own set of problems and may be difficult to implement between an existing, separate Eulerian and Lagrangian software system.

For example, to address blast-structure multi-disciplinary applications the blast component requires the solution of Eulerian and/or fluid dynamics approaches and the structure component requires the solution of Lagrangian and/or structural mechanics approaches. Solution of these applications involves high-pressure, high-strain, fracture/fragmentation coupled with blast, and/or high-strain-rate material interactions, where one or more of the material regions undergo relatively small deformations, while the other materials in the problem undergo arbitrarily large deformations. These applications are traditionally performed by transferring data files from one software package to another resulting in one-way coupling. Even this is very time consuming for addressing practical applications.

Zapotec[2] has done an impressive job at two-way coupling—CTH with Pronto3D—resulting in a single executable program that could be used in one-way coupling applications. For various reasons, however, some researchers prefer to use other Lagrangian codes like LS-Dyna as opposed to Pronto3D. In addition, Zapotec does not directly address the use of shell elements in the calculation.

The requirement of an end-to-end simulation capability for penetration-target interaction applications revealed the need for a seamless interdisciplinarycapability. An interdisciplinary capability can be addressed either by developing coupled software from scratch, or by integrating individual discipline validated software. The first approach involves

developing and validating the entire software spectrum, which is time consuming and may require more time to reach the end user. The second approach involves coupling existing, validated software for individual disciplines, which takes advantage of the tremendous "stove-pipe" developments already made in computer science and general computational sciences. This latter approach requires data management, seamless data movement, and robust modular scalable algorithms and is the central theme of this achievement. To address this problem, a research effort entitled "Interdisciplinary Computing Environment for Weapon-Target Interaction" was undertaken to produce an entirely new capability.

The uniqueness and significance of the research contribution in the newly developed Interdisciplinary Computing Environment (ICE) approach is the development of a common data hub. The common data hub is both a data model and data format. That means the information about the data values and 'how the data is used' are available. Known as the *eXtensible Data Model and Format* (XDMF), the data hub utilizes XML and HDF5 to provide a flexible yet powerful active data hub, as shown in Figure 1. The transfer of data is handled by a distributed shared memory system called Network Distributed Global Memory (NDGM). NDGM provides access to a virtual, contiguous buffer through a client-server architecture. A widely used hierarchical data format (HDF5) is used to provide an NDGM buffer with a structure. The common data hub facility provided by HDF5 and NDGM is effectively used to manage data between different software systems and effectively used to coordinate activities between different codes. This enables researchers and engineers to quickly couple production level parallel high performance computing codes from different disciplines and ultimately develop coupled algorithms and approaches for addressing both one-way coupled and fully coupled weapon-target interaction applications in a seamless way.
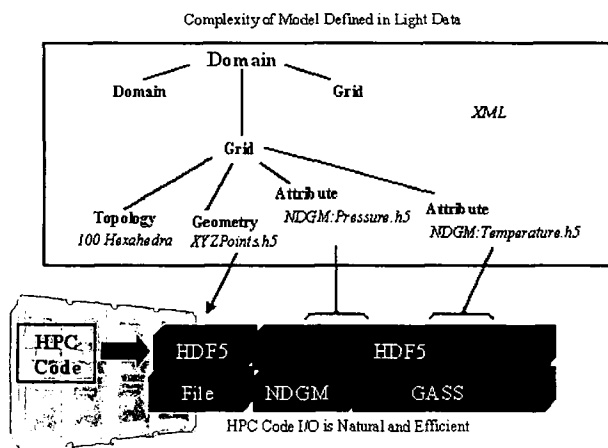

Figure 1. eXtensible data model and format

To address the requirement of one-way coupled land mine-vehicle structure interaction, this capability has been used to couple the finite element code LS-Dyna (a commercial software) with the finite volume shock physics code CTH (DoE software). This allows the strengths of both codes to be utilized to produce a result that is not possible by using each code separately. CTH is an excellent code for modeling the dynamic loading on a structure as a result of the detonation of an explosive and LS-Dyna is a much better code for simulating the large deformation of a thin structure such as a vehicle hull.

This type of one-way coupling is appropriate for this particular application because the deformation of the structure happens at a rate such that it has little effect on the developing blast, and the impact of the blast-driven fragmented soil on the structure is assumed to have a negligible effect. This approach was automated and used by ARL Weapons and Materials Research Directorate (WMRD) researchers to complete these analyses and assisted in not only improving designs and understanding of the mine blast-structure interaction, but also reduced the cycle time significantly.

Previous efforts have attacked the specific problem of coupling the Eulerian Shock Physics code CTH with Lagrangian Finite Element structural response codes. Typically, this involves the use of "tracer points" which is a specific feature of the Eulerian code and difficult to implement in the general sense. In addition, these methods did not address the problem of accurately representing complex geometries on the structured Eulerian mesh.

In addition to the scalable coupling methods, one of the technical challenges was to use consistent meshes for both software packages. The computational domains modeled by individual codes are entirely different and not easily coupled together. Note LS-Dyna is an unstructured finite element approach and CTH is a finite element-based structured mesh approach and typically armored vehicle hull structures are geometrically complex and represented using unstructured thin shell elements. LS-Dyna uses a representation called "shell elements" to represent thin structures. These elements have no thickness but accurately capture the deformations at a much lower computational cost than using many small hexahedral elements. CTH, being a finite volume code based on a structured mesh, has no concept of "shell elements". Introducing a structure composed of these elements into a structured mesh presents a technical challenge.

As shown in Figure 2, the method used to accomplish this task starts with giving these shell elements a thickness so they can be introduced into a structured mesh while still maintaining the shape of the thin structure. This is done by extruding each quadrilateral shell element in the direction opposite its "normal" direction (i.e.,

towards the inside of the entire structure). The resulting hexahedron are then decomposed into tetrahedron and converted into a data format that CTH can use for input.
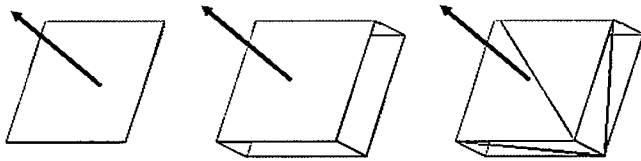

Figure 2. Shell elements are extruded to form tetrahedral elements

But a simple extrusion is sometimes insufficient. If the shell normals are used, problems arise if adjoining shell normal vectors differ significantly. In this case the back side of the extruded shell can extend beyond the surface of the adjoining shell, as depicted by the side view of the red and blue extruded shells below in Figure 3. To alleviate this problem, normal vectors are calculated on the nodes and averaged. New node positions are then calculated using these vectors, and the connectivity generated.
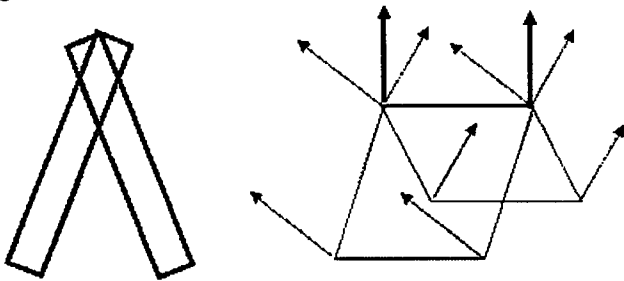

Figure 3. Normal vectors are averaged to represent the surface correctly

In addition to the newly generated geometry for material insertion, the CTH input consists of a description of the explosive charge and, potentially, soil to model the ground plane. CTH uses this information to simulate the detonation and calculates the pressure loads as they build on the structure. The pressure information for the entire mesh is saved to the common data model and format XDMF at regular intervals. Once the explosive has dissipated, the CTH calculation is halted.

Using the original thin shell structure, the pressure information is "probed" in order to generate a pressure vs. time history for each of the shell elements. That is, data is mapped, using interpolation, from the structured mesh onto points at the center of the shell faces. This information can then be input into the LS-Dyna calculation to simulate the structural deformation that will result from the explosion impinging on the vehicle structure. Sometimes the probed pressure observed directly on the surface can oscillate in the calculation. It is usually desirable to probe the pressure values just off of the surface. For this reason, the pressure values are sampled a small distance in the direction of the shell

normal vector, placing them into the blast field and off of the surface. This is depicted in Figure 4 below.
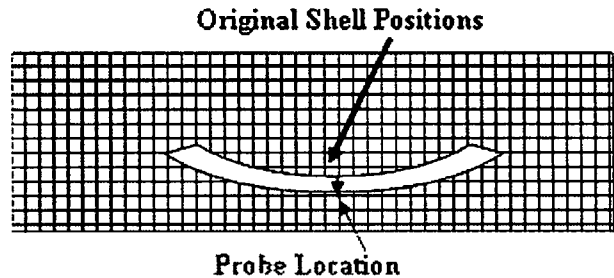
Original Shell Positions

Probe Location

Figure 4. Pressures are probed slightly off of the original surface

As a test case, a complex vehicle hull shape was taken from an LS-Dyna input file and converted using the previously described method. Figure 5 shows the original structure with an isosurface of the blast from CTH.

Since there were experimental results available for this configuration, the results of the entire simulation can be compared and potentially validated. To validate the coupling method itself, results were compared with simple geometries that could be accomplished with tracer point methods described earlier. Validation of the entire simulation will require validation of many factors including the blast and material models in both CTH and LS-Dyna.

The process was accomplished with the development of several scripts written in the Python scripting language. Python provides a convenient method to "glue" together many smaller software components. For example, access to XDMF, the Visualization Toolkit (vtk), and the various parsers are combined to create a single tool without re-compiling or linking any system code.
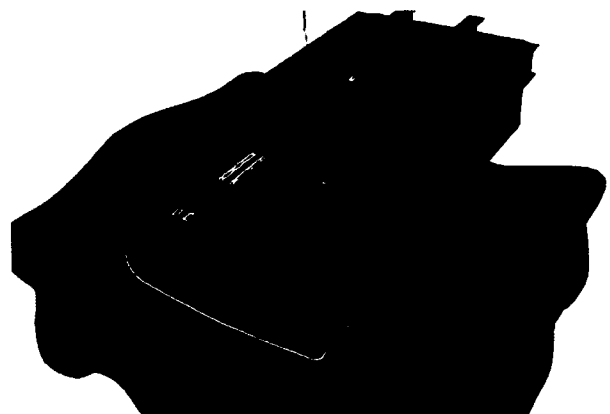

Figure 5. Mine blast interacting with vehicle hull

The first script accomplishes the parsing of the original LS-Dyna input and generates an XDMF dataset of the extruded tetrahedral mesh. The next script uses this mesh as input and generates both the CTH input file and

the ExodusII file needed for material insertion. The last script processes the CTH output and generates the pressure time histories and formats them for input to LS-Dyna.

The Interdisciplinary Computing Environment for Weapon-Target Interaction provides a new capability for the physics based simulation of weapon-target interactions. This new capability is being used at the US Army Research Laboratory (ARL) in armor/anti-armor designs and survivability of new systems against land-mine threats.

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