Coupled Fluid / Structure Interaction Simulation Using Abaqus CEL

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For a system which involves a fluid medium contained inside a deformable structure, such as a fuel tank system, a simulation which couples the structure and fluid may be required depending on the system performance metric of interest. Simulation methods for fluid / structure interaction (FSI) have been gradually developed by CAE engineers since the advent of increased computing power. A limitation in using previous FSI simulations is the dynamic event time period that the FSI method can simulate. With the new CEL function, Abaqus can simulate a coupled fluid / structure dynamic event of several seconds real-time duration in days instead of weeks as compared to other available software. Abaqus/Standard and Abaqus/Explicit CEL function can be used to create a seamless fuel tank system simulation method to assess the fuel tank assembly and road loading performance.

Keywords: sloshing, coupled Eulerian-Lagrangian, fluid / structure interaction (FSI)

1. Introduction

When a vehicle is accelerating or decelerating on a road surface, the fuel inside a fuel tank sloshes, and the moving fuel exerts pressure on the fuel tank surfaces. This transient hydrodynamic pressure is also transmitted to the fuel tank straps and the supporting body/frame structure in contact with the fuel tank shell as well as components inside the fuel tank. The consequences are that the following vehicle performance may be affected: (1) airborne and structure-borne slosh noise and (2) fatigue life of the fuel tank, straps, and components inside the fuel tank. For such a fuel tank system, a simulation which couples the structure and fluid may be required. One of limitations in using existing FSI (Fluid Structure Interaction) simulations is the dynamic event time period that the FSI method can simulate within an acceptable turnaround time.

The new pure Eulerian analysis capability in Abaqus/Explicit allows effective modeling of applications involving extreme deformation, including fluid flow. The Eulerian capability can be coupled with traditional Lagrangian capabilities to model interactions between highly deformable materials and relatively stiff bodies, such as in fluid-structure interactions. This new capability is called the Coupled Eulerian-Lagrangian (CEL) function and was released by Simulia in Abaqus 6.7EF. With CEL, fluid sloshing can be handled effectively using Eulerian analysis and the tank structure can be modeled using traditional nonlinear Lagrangian analyses. Eulerian-Lagrangian contact in CEL allows the Eulerian materials to be combined with Lagrangian analyses. With the new CEL function, Abaqus can simulate a dynamic FSI event of 3 seconds real-time duration in about 55 hours using 16 CPUs. This solution time is impossible to achieve when using other software.

To demonstrate the newly developed Abaqus CEL capability, an integrated fuel tank system simulation technique is presented in this paper. The simulation involves (1) assembly of the fuel system, (2) initializing gasoline in the fuel tank and (3) applying service loading to the fuel tank system.

2. CEL Solution

An explicit dynamic procedure in the finite element method is employed in CEL. The governing equations consist of the conservation laws of mass, momentum and energy and the constitutive equations. The governing equations are integrated in time under the Eulerian coordinates.

An Eulerian material can be modeled as viscous compressible Newtonian fluid:

$$\boldsymbol{\sigma} = -p\mathbf{1} + 2\eta\dot{\mathbf{e}}$$

where $\boldsymbol{\sigma}$ is the Cauchy stress tensor, p is the pressure, η is the shear viscosity and $\dot{\mathbf{e}}$ is the strain rate.

Fluid-Structure Coupling is achieved by using the Abaqus/Explicit general contact definition.

3. Modeling

3.1 Modeling the Eulerian Domain

The Eulerian mesh is shown in Figure 1. The materials representing the fuel can flow during the analysis, and the mesh does not need to conform to the topology of the materials; in fact, a simple rectangular grid typically provides the best results.

In a traditional Eulerian analysis, material flows through an Eulerian mesh that is fixed in space. Since it is stationary, the Eulerian mesh must be large enough to enclose the entire trajectory of interest, for example, the Lagrangian domain. In the case when the Lagrangian domain moves with a velocity, thus resulting in a trajectory that can be long, a large Eulerian mesh whose elements are mostly empty is required. In the newly released Abaqus 6.9EF, an Eulerian mesh motion feature (*Eulerian Mesh Motion) is added to allow the Eulerian mesh to move in space to enclose a target object. This can greatly reduce the mesh size required and, hence, the simulation solution time and cost.

The Eulerian material which represents the gasoline inside the fuel tank is modeled as a viscous Newtonian fluid. The density of the fluid is 7.6×10^2 kg/m^3, the coefficient of viscosity is 5.7×10^{-4} (kg/m·s), and the sound wave speed is 1.147×10^3 m/s.

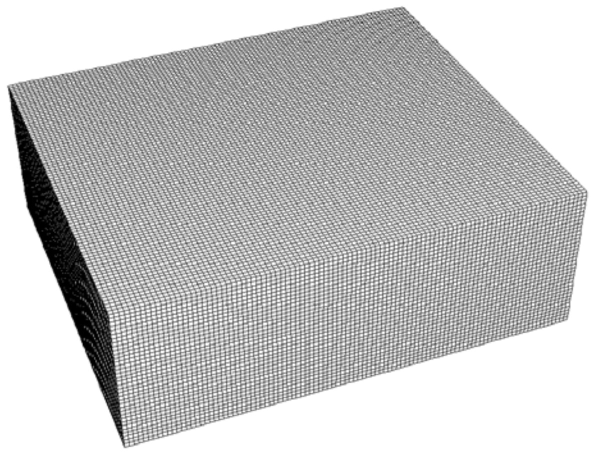

Figure 1. Eulerian mesh

An Eulerian section assignment defines the materials that may be present in the mesh over the course of the analysis, and an initial condition specifies which materials are present in each element at the beginning of the analysis (an element may be partially filled with a material). The initial condition effectively determines the initial topology of the materials in the model. Figure 2 shows the initial condition of the fuel inside the fuel tank. The tank illustrated is for a typical All Wheel Drive application which has left and right lobes which contain fuel.

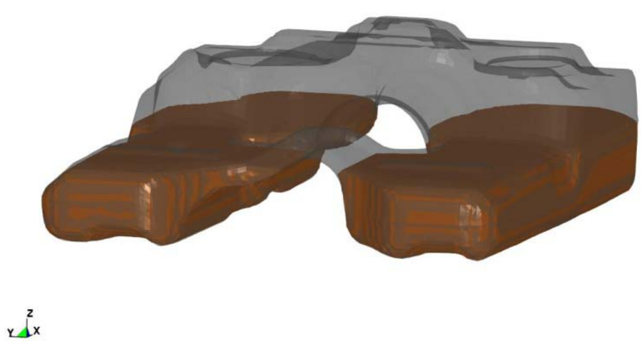

Figure 2. Eulerian material initialization

3.2 Modeling the Lagrangian Domain

The tank and underbody structure can be modeled using traditional nonlinear Lagrangian elements (shell, connector, etc.), as seen in Figure 3. This example consists of a fuel tank, tank shield, and straps, plus underbody floor, cross members and rails.

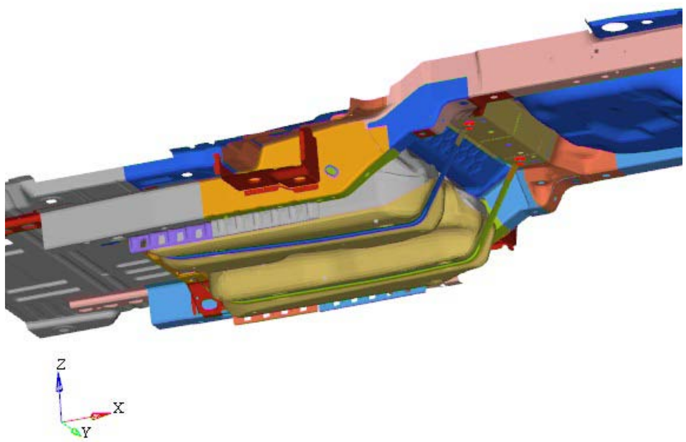

Figure 3. Tank and Underbody Structure Lagrangian Mesh

2.3 Modeling Eulerian-Lagrangian Contact

The Eulerian-Lagrangian contact formulation is based on an enhanced immersed boundary method. In this method, the Lagrangian structure occupies void regions inside the Eulerian mesh. The contact algorithm automatically computes and tracks the interface between the Lagrangian structure and the Eulerian materials. A great benefit of this method is that there is no need to generate a conforming mesh for the Eulerian domain.

A friction property is introduced into a mechanical surface interaction model governing the interaction of the contact surfaces. A friction coefficient of 0.12 is used in the simulation.

4. Fuel Tank Assembly and Slosh Simulation Example

4.1 Tank Assembly Step

In this step, there is no need for modeling the Eulerian mesh. The fuel and underbody structural model consists of only Lagrangian elements. The assembly of the fuel system to the vehicle frame/body is achieved by using the *PRE-TENSION function of Abaqus/Standard. The stresses/strains/displacements etc. as result of assembly of the fuel system (Figure 4) are stored in the restart files.

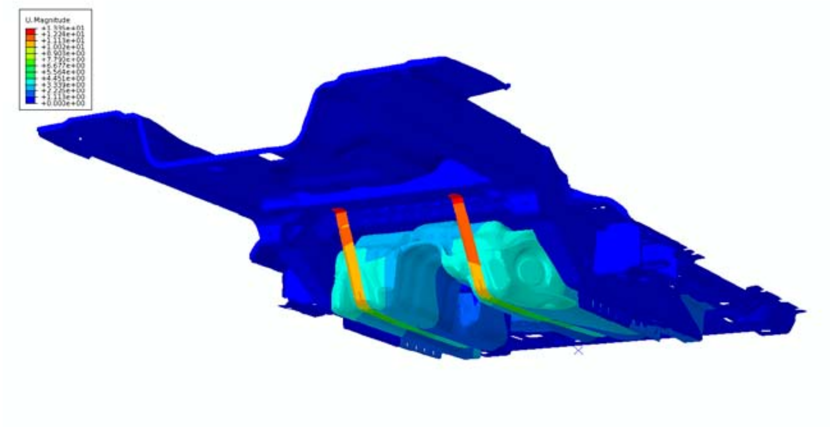

Figure 4. Assembly-induced displacement of the fuel system

4.2 Fuel Initialization Step

The Eulerian mesh and the Eulerian-Lagrangian contact are added to the FE model of the fuel tank from the previous step. To initialize 16.0 gallons of gasoline in the assembled fuel tank, the Volume Fraction tool in Abaqus/CAE can be used (as shown in Figure 5). A GM internal tool can be used for the same purpose.

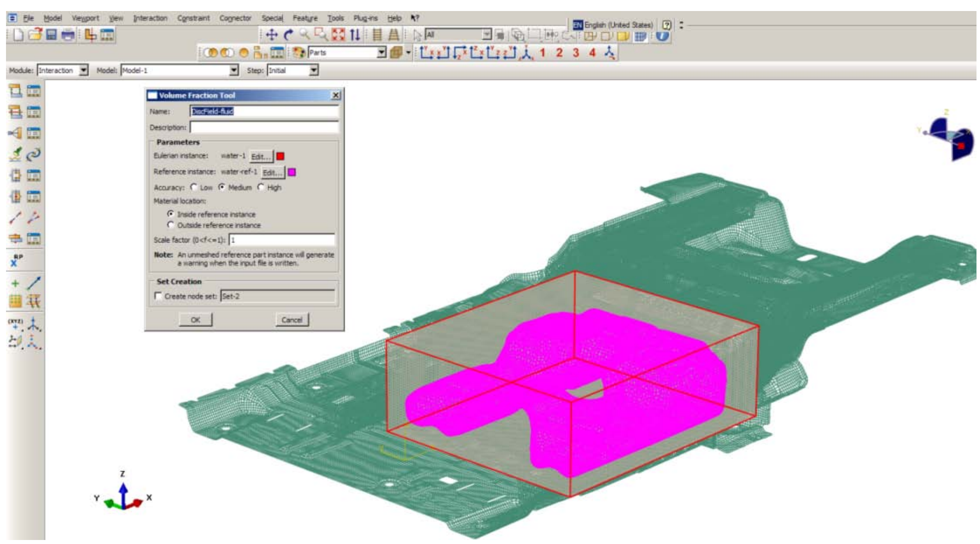

Figure 5. Volume Fraction tool in Abaqus/CAE

4.3 Fuel Sloshing Simulation Step

The restart/import procedure is carried out after the fuel filling step. The deformed tank mesh and its associated material state from the Abaqus/Standard assembly step are transferred into Abaqus/Explicit. In the meantime, the fuel inside the tank has been included into the model by defining an Eulerian mesh initialized with gasoline.

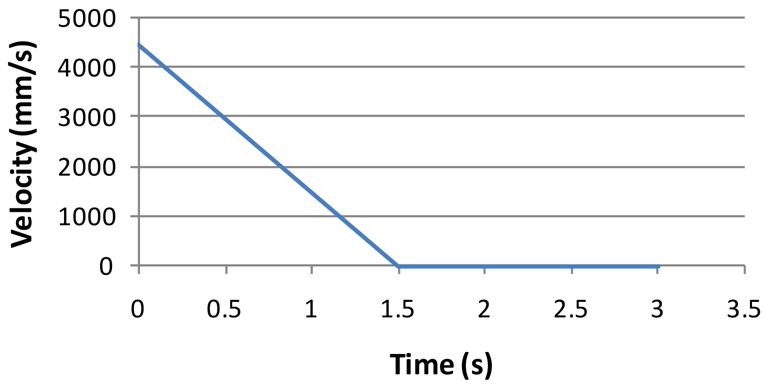

Figure 6. Velocity loading

4.4 Results

The slosh event simulated for this fuel tank system is 3 seconds of moderate vehicle deceleration using a velocity time history as input (Figure 6). The Eulerian mesh motion feature (*Eulerian Mesh Motion) is engaged to allow the Eulerian mesh to move in space to enclose the fuel tank. The total number of Lagrangian elements is 167,000. The Eulerian mesh represents the fuel fluid domain with 300,000 elements. The simulation was carried out on a Linux/x86-64 platform with 16 CPUs. The simulation took 55 hours to solve. This example demonstrated that with the Abaqus CEL function, the FSI simulation method can be used for an integrated fuel tank system slosh simulation.

Figure 7 shows the gasoline, fuel tank and the fuel tank subsystem interactions. The detailed gasoline flow patterns at 1 second and 2 second are shown in Figure 8 and Figure 9, respectively. The vertical displacement of the fuel system at 1.5 second is shown in Figure 10.

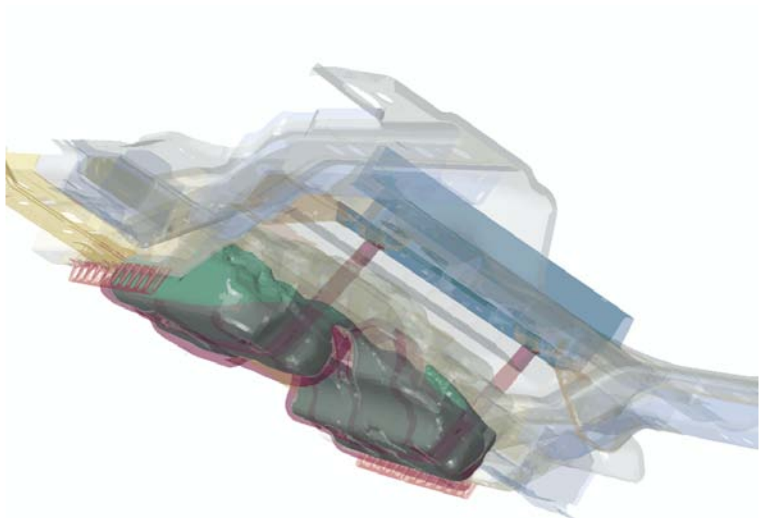

Figure 7. Flow pattern at 1.0s showing the fuel tank assembly

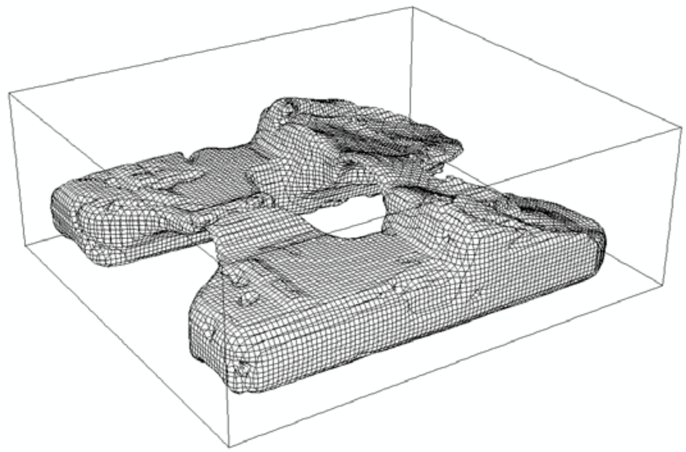

Figure 8. Fuel flow pattern inside the fuel tank at 1.0s

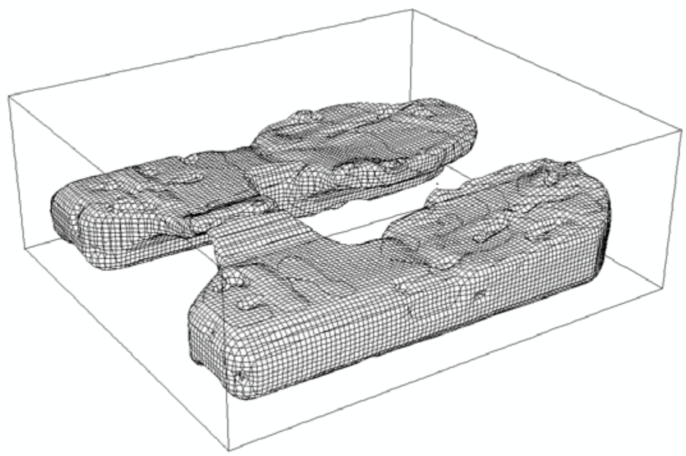

Figure 9. Fuel flow pattern inside the fuel tank at 2.0s

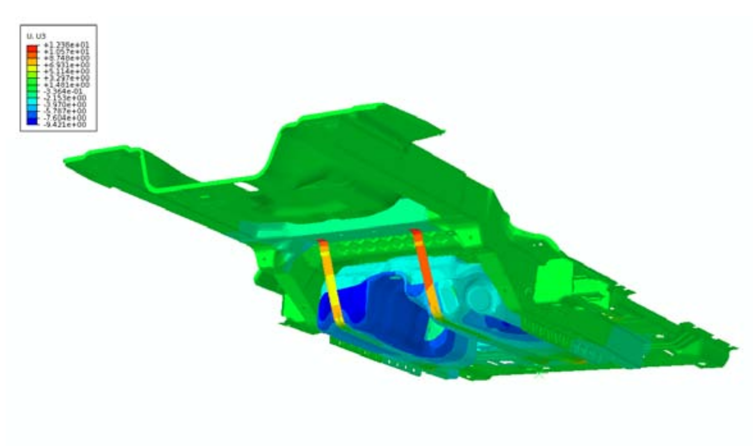

Figure 10. Vertical displacement of the fuel system at 1.5s

5. Conclusion

Using Abaqus CEL, one can not only study the fuel slosh flow patterns, but also the stresses/strains/displacements etc. induced by the sloshing. Abaqus/Standard with the Abaqus/Explicit CEL function can be used to create a seamless fuel system simulation method. With Abaqus' outstanding performance, it is possible to solve a FSI simulation such as a fuel tank slosh durability.

6. Reference

1. Abaqus Version 6.9 Documentation, Dassault Systemes Simulia Corp., 2009

7. Acknowledgement

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