Modeling of Vehicle Fuel via Smoothed Particle Hydrodynamics (SPH) Method in LS-DYNA® for Vehicle Crash Virtual Simulation

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Abstract

This paper describes advantages of modeling a fluid in a vehicle fuel tank using the Smoothed Particle Hydrodynamics (SPH) method in vehicle crash computer aided engineering (CAE) simulations in order to achieve appropriate fuel/fluid behavior during a crash event. SPH is a mesh free Lagrangian particle fluid modeling technique used for simulating fluid flows, whereas, the legacy CAE modeling method uses a solid tetra element mesh with MAT1F MAT_ELASTIC_FLUID to model the fluid in the fuel tank. The SPH method has many advantages over the legacy modeling method in terms of capturing important fuel tank responses, such as: correct tank internal fluid pressure, proper tank shell deformation, and tank clearances to the surrounding environment. Accurate simulation of these are important to meet NHTSA FMVSS 301 and fuel system integrity requirements.

To compare the responses from the fuel tank, a study has been carried out by comparing SPH and legacy CAE methods with a physical test. The internal fluid pressure at the fuel tank control valve from a 35 mph flat frontal rigid barrier impact CAE model was plotted against a physical sled test that corresponds to the 35 mph flat frontal rigid barrier impact event. It was found that the SPH method provides better correlation over the legacy modeling method. In addition, tank shell deformation and tank clearances for both methods were compared with the physical sled test; It has been observed that the SPH method provides a more accurate tank shell deformation when compared to the legacy modeling method. There is an increase in computation time for the SPH method, however, this method ensures the result accuracy during fluid structure interaction.

Introduction

Fuel system integrity requirements and compliance to NHTSA FMVSS 301 fuel system requirements are critical for vehicle safety and a successful vehicle launch. As per FMVSS 301, fuel tank is required to have fuel-leakage prevention structure even if a collision occurs [1]. Therefore, in order to design structures and specifications which eliminate the risk of fuel spillage, it is necessary to predict responses of the vehicle and fuel tank at an early development stage. Vehicle development cycles are becoming more compressed and continue to depend more on virtual simulation and validation. Accurate CAE modeling of the fuel in the fuel tank for fluid-structure interaction (FSI) is critical to identify potential issues early in the design cycle. Otherwise, engineers must wait for completion of the tooling to receive physical parts for component or vehicle testing. This is a long process, on the order of 28-36 weeks to get blow molded fuel tank physical components. It becomes even more challenging when trying to make a design change late in the development cycle, or late during vehicle testing.

It now appears that the confluence of many advances in CAE technology have made it possible to more accurately model vehicle fuel via smoothed particle hydrodynamics (SPH). These include: improvements in the SPH method, the LS-DYNA solver implementation, the pre-and-post processing software, and the computing horsepower necessary to solve the numerical simulations in a reasonable time. Virtual simulation results using SPH can be used to validate or to help improve designs. It also helps in identifying potential fuel system integrity issues earlier in the vehicle development cycle. Modeling fuel with SPH is one of the three methods of modeling a fuel in the fuel tank. The other fluid simulation methods are ALE (Arbitrary Lagrangian Eulerian) and incompressible CFD (Computational Fluid Dynamics) [2]. Along with the fluid modeling, it is important to consider other fuel system modeling approaches such as: fuel tank shell modeling, tank shell material model, strap modeling, and other fuel system components modeling like fuel lines, valves, fuel pump sending unit, etc. These items are also important in order to get the proper fluid behavior during the simulation but not included in the scope of this paper.

The legacy method of modeling vehicle fuel has a mesh, whereas, SPH is meshless [3]. For comparison of the legacy and proposed SPH fuel modeling methods, a straightforward laboratory sled test containing an enclosed filled fuel tank has been carried out and compared to the 35 mph flat frontal impact simulation. In general, the sled test mimics the vehicle deceleration (g) pulse from the 35 mph flat frontal impact event.

Apart from the advantages of the SPH method, this paper also explains how to model the SPH particles using the pre-processor ANSA and the keywords necessary for the implementation in LS-DYNA solver. A main difference between legacy method and SPH is the absence of a mesh, which makes SPH ideally suited to simulate problems dominated by complex boundary conditions, like free surface flows, or large boundary displacement [4]. In the SPH method, the particles are in the computational framework on which the governing equations are resolved. The resolution of the SPH method can easily be adjusted with respect to variables such as density [4]. There are many applications of SPH in the case of fuel system integrity. Its implementation is related to: Incompressible fluids, sloshing/splashing, and fluid-structure interaction.

Background

The fuel tank is attached to the vehicle with straps. Standard fuel tank shell construction is 6 layers of composite - out of which, 2 layers are to reduce the vapor loss. Usually a minimum tank shell thickness is 3.0mm, however, the tank shell thickness is variable due to geometry and the blow molding process. There are several fuel system components mounted to the tank shell, including, the fuel filler and rollover valve. These valves have their pressure requirements.

The fluid/fuel sloshing phenomena is present in a partially filled tank due to a sudden acceleration/deceleration during an impact event. Internal tank fluid pressure is a function of acceleration/deceleration (g) loading, and to a lesser extent, it's a function of tank motion with respect to the vehicle. During a 35 mph flat frontal rigid barrier impact event, the vehicle experiences a deceleration of around 45g's. This will result in an increase in the internal tank pressure as a result of fluid sloshing. If this exceeds the valve's internal pressure threshold, there is a potential risk of fuel spillage through valves of fuel system.

Internal fluid pressure inside the tank can also cause bulging deformation of the fuel tank shell [2,3]. Tank shell bulging can reduce dynamic clearance of fuel system components to the surrounding vehicle environment/components. There are guidelines that exist for minimum dynamic clearance for fuel system integrity.

Proper tank bulging captures more realistic plastic strains in the tank shell. These plastic strains are monitored for the integrity of the fuel tank shell. These potential issues can be addressed early in the vehicle development cycle through simulation by implementing the SPH method. The simulation is conducted using LS-DYNA solver, general purpose nonlinear finite element software.

Current/Legacy method

In the legacy method, fluid/fuel is modeled with a solid tetra element mesh with 10 to 12mm mesh size as shown in Figure 1.

a) Tetra fuel in fuel tank **b) Tetra mesh pattern**

Figure 1 - Legacy fuel modeling method with tetra mesh

FMVSS 301 requires the tank to be 90% full of fuel, so the appropriate tank volume is filled with a tetra mesh to represent the fluid. The Fluid is assigned with *MAT 1F MAT_ELASTIC_FLUID with gasoline fluid properties as shown in Table 1.

Mass density (ρ)	6.999E-7 kg/mm3
Young's modulus (E)	0.001 Gpa
Poisson's ratio (PR)	0.3
Bulk modulus (K)	0.83 Gpa
Tensor viscosity coefficient (VC)	0.25
Cavitation pressure (CP)	Default

Table 1: Legacy method fuel properties

As shown in the Figure 2, the legacy method does not capture fluid sloshing in the tank. It roughly captures mass and inertia of the fluid in the fuel tank, which is important for the vehicle level response in the event of crash.

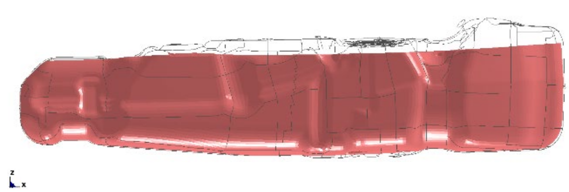
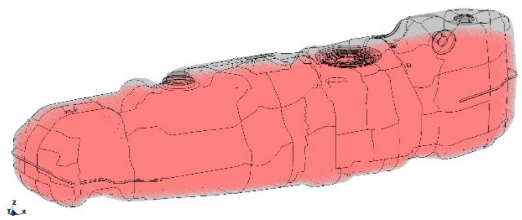


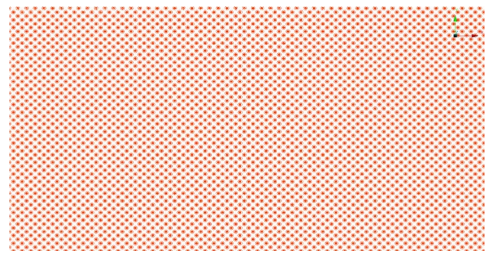
Figure 2 - Legacy method fluid behavior at t=100 ms (no sloshing observed)

SPH method

The modeling of the SPH fluid particles was carried out using BETA CAE ANSA's "Tank" module as shown in Figure 3. This module generates SPH elements of a given volume within a closed shell mesh. Total solid volume and radius should be specified in liters for the spherical SPH elements to be generated [5]. The Total weight of the fluid (SPH) is adjusted to an equivalent weight of the gasoline. This can also be done using ANSA.



a) SPH fuel in fuel tank



b) SPH particle pattern

Figure 3 - SPH fuel modeling method

The nodes for the SPH elements will be uniformly spaced in the three dimensional space. To represent the interface between the fluid and the tank shell in LS-DYNA, a "Nodes_To_Surface" contact interface was selected [6]. In this LS-DYNA contact definition, a group of nodes are defined as the slave side and master segments (shell elements) are defined for the master side. The nodes are checked against the segments and if penetration is detected, equal and opposite forces are applied to the slave and master sides to overcome these penetrations [3, 6]. In the CAE model, all fluid (SPH) nodes are used as the slave side and the shell elements from the tank shell are used as the master side.

The SPH is assigned *MAT_NULL material with gasoline fluid properties as shown in Table 2.

Mass density (ρ)	6.999E-7 kg/mm3
Pressure cutoff (PC)	-1E10 Gpa
Dynamic viscosity coeff (MU)	8.7E-10
Relative volume in tension (TEROD)	Default
Relative volume in compression (CEROD)	Default
Young's modulus (YM)	0.001 Gpa
Poisson's ratio (PR)	0.3

Table 2: SPH method fuel properties

As shown in Figure 4, SPH method captures the fluid sloshing behavior in the tank.

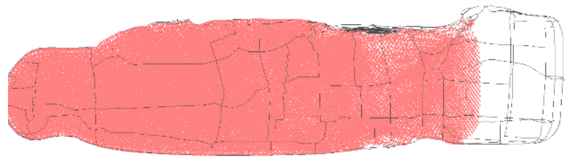


Figure 4 - SPH method fluid behavior at t=100 ms (sloshing observed)

In order to get the proper fluid behavior in the simulation, a few additional LS Dyna keywords are required as below.

**CONTROL_MPP_DECOMPOSITION_DISTRIBUTE_SPH_ELEMENTS*

**CONTROL_SPH*

```
ncbs  boxid     dt      idim    memory      form     start      maxv
  10      0  1.E20         3     10000        15       0.0     1.E15
cont  deriv    ini     ishow     ierod     icont     iavis
   0      0      0         1         0         0         1
```

**EOS_GRUNEISEN*

```
eosid      c     s1     s2     s3     gamao      a       e0
    1   1500    0.0    0.0    0.0       0.0    0.0      0.0
   v0
  1.0
```

**HOURGLASS* (SPH Hourglass control)

```
HGID     HIQ      QM      IBQ      Q1       Q2      QB      QW
  13       1    0.01        0   0.001   1.E-12     0.1     0.1
```

Simulation setup

The simulation setup was carried out on a full vehicle CAE model for a 35 mph flat frontal rigid barrier test mode to obtain pulse for the physical sled test. A full vehicle CAE model has been created using ANSA with impact/crash specific modeling guidelines and parameters. Two separate simulation setups were created with SPH and legacy fluid modeling methods. Several generic and fuel system specific output parameters are generated from the simulation at different time intervals. Some of the key fuel system specific output parameters include: vehicle pulse, rollover valve pressure, tank shell plastic strains, acceleration, displacement and velocities of fuel system components.

Test setup

The physical sled test setup contains the fuel tank, its components, and also includes a cut-away of the vehicle frame structure as shown in Figure 5.

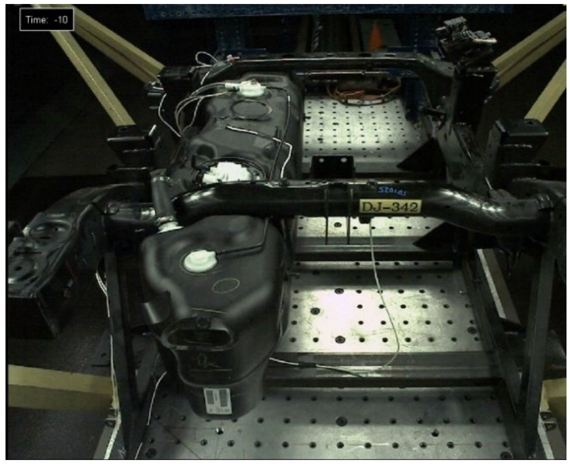


Figure 5 – Physical sled test setup

The tank is filled with 90% water/fluid as per FMVSS 301 requirement and the sled setup has pressure sensors to capture internal fluid pressure on the fuel tank valves. It is also equipped with high speed cameras to record the tank deformation time history. A pulse from the 35 mph flat frontal rigid barrier impact CAE model as shown in Figure 6, is fed to the physical sled test in order to mimic fuel tank behavior.

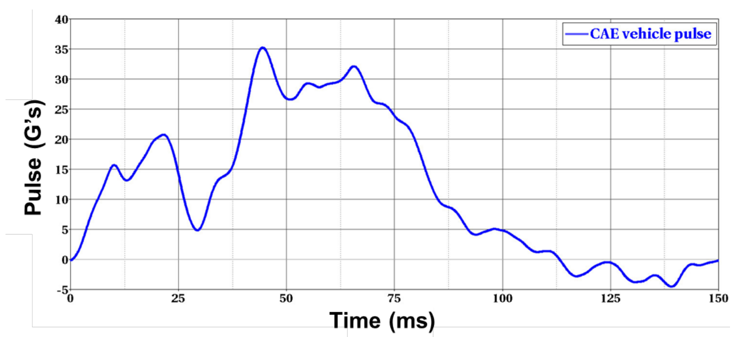


Figure 6 – Average vehicle rear sill pulse

Results

Test to CAE result comparisons have been made for Internal fluid pressure, tank deformation, and tank clearances with surrounding components.

The legacy tetra mesh modeling method produced a peak 3.6 psi internal fluid pressure and no internal fluid pressure profile. The meshless SPH method however properly captured the internal fluid pressure as measured in the physical test. The SPH method predicted the peak internal fluid pressure to be 70 psi, versus 71 psi as measured in the physical sled test – it matches the profile as shown in the Figure 7.

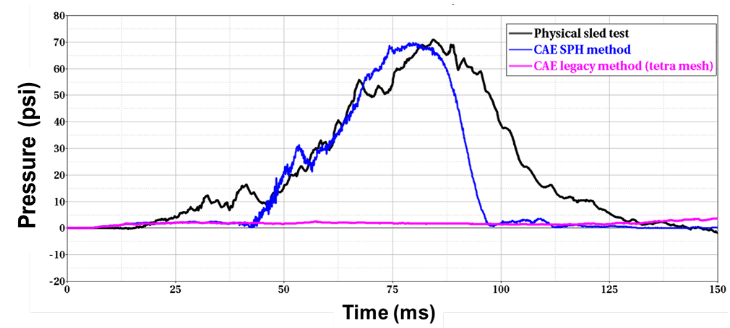
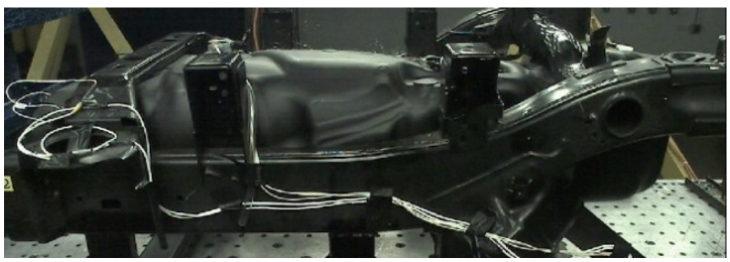
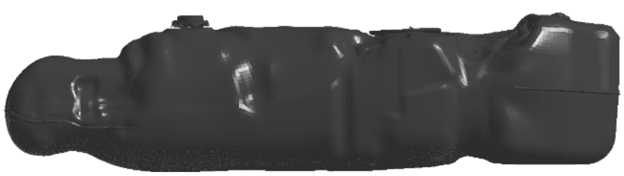


Figure 7 – Fuel tank rollover valve pressure from simulation

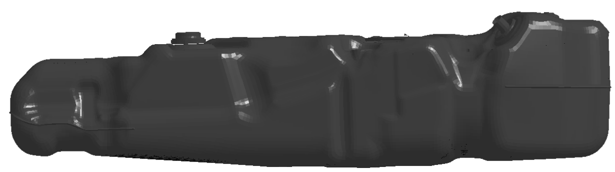
Furthermore, the SPH method captured the bulging in the tank shell which results in the proper tank shell deformation when compared to the physical sled test as shown in Figure 8. This accurately reflects the material plastic strain of the tank shell. Monitoring of material plastic strain on the tank shell is one CAE metric then can be used to selectively thicken areas, or make design changes in the tank shell geometry.



a) Physical sled test (tank shell bulging observed)



b) SPH model (tank shell bulging observed)



c) Legacy model (no tank shell bulging)

Figure 8 - Fuel tank deformation comparison

In turn, the tank shell bulging in SPH CAE model results in more accurate dynamic clearance measurements between fuel system components and the surrounding structure.

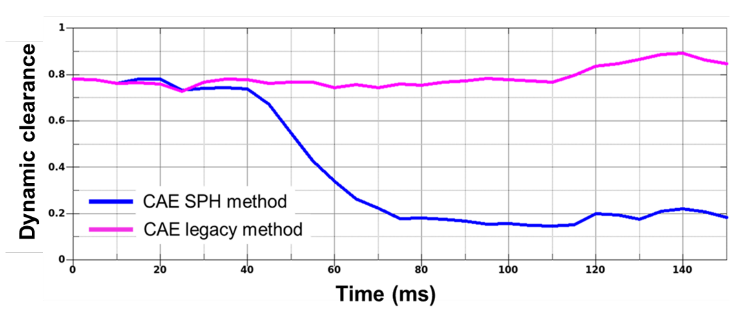


Figure 9 – Dynamic clearance (fuel tank to frame components)

The above Figure 9 shows the fuel tank to frame components dynamic clearance comparison between CAE SPH and CAE legacy methods. It can be observed that with the SPH method, the gap is reducing between the tank and surrounding frame components because of the tank shell bulging effect. Since the legacy method does not give proper tank shell bulging, it does not capture the gap reduction between tank and surrounding frame components. This gap reduction measurement was not obtained on the physical sled test, but observed in high speed video.

Summary and conclusion

A finite element model with the smoothed particle hydrodynamics (SPH) algorithm in LS-DYNA is employed to simulate the behavior of fuel/fluid in a fuel tank in the 35 mph flat frontal impact event. This study shows that use of the SPH method to model fuel/fluid in a fuel tank successfully captures the sloshing phenomenon that occurs when a vehicle experiences sudden acceleration or deceleration during an impact event.

This is the key to the proper representation of the internal fluid pressure, tank deformation, and dynamic clearance measurement with surrounding vehicle components. These potential issues related to fuel system integrity can be brought to attention early in the vehicle development cycle by implementing the SPH method into vehicle simulations.

Implementation of the SPH method in vehicle crash simulations comes at the expense of a higher computing cost and longer simulation run times which may not seem like an advantage. However, When the focus of the vehicle crash simulation is structural integrity, or occupant related, then analysts may simply choose to continue to use the legacy tetra mesh for the fuel modeling. But, when the singular focus of a vehicle crash simulation is fuel system integrity, the authors believe that the computing time is well spent to have a more accurate/correct fluid-structure interaction in the fuel tank.

References

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