Simulation of Automotive Fuel Tank Sloshing using Radioss

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Abbreviations:
SPH- Smooth Particle Hydrodynamics
FEA- Finite element Analysis
FE- Finite elements

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Sloshing, SPH method, Road Load Data,

Abstract
Fuel tank is subjected to various dynamic conditions during running of the vehicle. While in the development stage, various experiments are required to assure that the design qualifies under various dynamic load cycles. These experiments include virtual simulations and many types of physical tests. This work is an attempt to virtually simulate the fuel sloshing in the tank under dynamic loadings as per test setup. This paper demonstrates implementation of a powerful numerical analysis tool SPH, available in Altair Radioss for automotive fuel tank application.

As the fuel is in the liquid state and this liquid mass affects the design of fuel tank due to its motion under various dynamic conditions, the sloshing belongs to a class of multi-physics problems.

It becomes important to ensure structural integrity of fuel tank and effectively reduce noise levels caused by fluid motion inside the fuel tank by designing baffles and separators to control the sloshing flow pattern.

The Altair Radioss, SPH method is used to simulate the fluid motion and Fatigue evaluation is performed to estimate the fatigue life of the tank.

Introduction
Sloshing refers to movement of the liquid (fuel) inside the structure which is also undergoing motion. The liquid must have a free surface to constitute a slosh dynamics problem, where the liquid can interact with the structure (in this case fuel tank) to alter the system dynamics significantly. Different types of dynamic environments are possible in an automobile normal running as well as during typical driving conditions such as panic breaking, pothole, sudden acceleration, cornering etc. Sloshing is undesired because it produces noise, high impact force on the tank walls and challenge of the low fuel handling. The presence of baffle dissipates the energy that is induced by the fuel motions. Extensive mathematical and empirical relationships have been developed to describe liquid slosh. Important examples include fuel tanks in automobile, propellant slosh in spacecraft & rockets. In cargo, slosh in ships and in trucks transporting liquids. Sloshing phenomenon is mainly observed in partially filled tanks (structure) and is more pronounced when vehicles experience sudden acceleration or deceleration.
Process Methodology

*Flow chart for analysis*

Below figure illustrates the steps that are followed in simulating sloshing phenomenon.

![Flow chart for analysis](image)

*Figure 1: Flow chart of analysis.*

*Physical test set for Simulation of Sloshing*

Figure 2 show the slider crank mechanism used to generate sinusoidal motion to the base table on which the fuel tank is mounted. Input is given in the form of imposed displacement.

![Physical test set for sloshing simulation](image)

*Figure 2: Physical test set for sloshing simulation*

Test is carried out in two test conditions, i.e. Completely filled fuel tank and half filled fuel tank. In this paper, half filled fuel tank is simulated to meet the requirements.

*Geometry details:* - Fuel tank consists of two baffles to guide and control the fluid flow which are welded to top shell. Top and bottom shell encloses the volume and are joined at strip. Figure 3 shows the geometry details of the fuel tank assembly.

![Geometry details](image)

*Figure 3: Geometry details*
FE Model details

Shell elements are used to generate finite element model and the welding of the baffle with top shell is represented using spring type beam (type 13) elements. Figure 4 shows the FE Model. The upper strip and lower strip are merged in a single component to avoid small size elements. This will help to overcome small time step problem.

![Figure 4: FE model.](image)

There are mainly four formulations to deal with simulation of fluid structure interaction

1. Lagrangian formulations
2. Eulerian formulations
3. Arbitrary Lagrangian-Eulerian formulation (ALE)

Lagrangian formulation is mainly used for describing a solid mechanics problem. The problem is described by a high number of mass particles, where the motion of every single particle is being observed in space and time. Finite elements partly move and deform.

In Eulerian formulations, the problem is being observed at one point in space which does not follow the motion of the single particle. In one time step, several mass particles may pass the observed point. Material also flows through the finite elements. CPU time required is more.

In Arbitrary Lagrangian-Eulerian formulation (ALE), the mesh partly moves and deforms because it follows the material (Lagrangian formulation), while at the same time the material can also flow through the mesh (Eulerian formulation). Quality of the results is not much accurate. CPU time required is more.

Above three formulations are based on the particle physics theory.

The forth one, Smooth Particle Hydrodynamics (SPH) is a mesh-less numerical method based on the interpolation theory. It allows any function to be expressed in terms of its values at set of disordered points so called particles. The SPH method implemented in RADIOSS in Lagrangian approach in which, the motion of a discrete number of particles traced in time domain. SPH is complementary approach with respect to ALE method. When the ALE mesh is too distorted to handle good results, SPH method may allow getting a sufficiently accurate solution. It requires less CPU time compared to above three formulations. Smoothed Particle Hydrodynamics (SPH) is mesh free adaptive Lagrangian particle method for modeling fluid flows, was first invented by Lucy in 1977 to solve astrophysical problems in three dimensional open spaces, in particular polytropes.

In SPH, concept of ‘net’ is used inline with mesh. Net is nothing but, mapping of particles in space as representation of fluid as shown in Figure 5. ‘A cubic centered faces net’ realizes a hexagonal compact distribution and can be useful to build the net. The mass of the particle can be represented using following equation.

\[ m_p \approx \rho \times \frac{V}{n} \quad - - - - (1) \]

where \( m_p \) = Mass of particle. \( \rho \) = Density of the fluid. \( V \) = Total Volume of the SPH Particles \( n \) = Number of SPH particles.

The normal values \( h_0 \) is, the distance between any particle and its closest neighbor compact net, with respect to the following equation.

\[ h_0^3 \approx \left( \frac{\sqrt{2} \times m_p}{\rho} \right) \quad - - - - (2) \]

where \( m_p \) = Mass of particle. \( \rho \) = Density of the fluid.
Since the space can be portioned into polyhedras surrounding each particle of the net, each one with a volume. This is \( V_p \) calculated from equation \( 1 \) and \( 2 \) as,

\[
V_p = \frac{h_0^3}{\sqrt{2}} \quad \cdots \text{ (3)}
\]

where \( V_p \) = Volume of particle

Figure 5: Local view of hexagonal compact net and perspective view of cubic centered faces of net.

Smooth Hydrodynamics particles are generated within the required volume in the fuel tank. Figure 6 shows the representations of SPH elements and imposed displacement points are shown in Figure 7.

Figure 6: SPH representation inside the tank.

Figure 7: Boundary condition

The displacement is given to four mounting holes in longitudinal direction along length of the tank. The representative input is shown below in figure 8.

The nonlinear material property and material stress strain curve used for analysis is representatively shown in the figure 9.

Figure 8: Imposed displacement.

Figure 9: Stress strain curve

Following are the FE Model details.

- Number of 2D-elements: 11675
- Number of nodes: 11622
- Number of SPH elements: 39286
- Number of rigid: 4
- Number of weld (spring type beam): 22
- Total number of elements: 50987
- Total number of nodes: 50953
Results & Discussions

The explicit non-linear analysis is carried out using Radioss solver for 1 cycle. The envelope for the all time steps of maximum stress plots are shown in the Figure 10, for top and bottom shells similarly in Figure 11, for inner baffles.

![Figure 10: Stress plot for Top & Bottom shells](image)

![Figure 11: Stress plot for baffles](image)

The Figure 12 shows energy plot for the simulation. The hour glass energy is less than 1% of the total internal energy, which confirms the accuracy of the analysis.

![Figure 12: Energies plot](image)

Life prediction

Fatigue life evaluation of fuel tank is carried out by using stress history output from the Radioss solver, which is transformed to required ASCII input for the Fatigue estimation. Appropriate fatigue material properties of fuel tank material are used for life assessment. Figure 13 shows FE model used for fatigue evaluation and location of minimum life in repeats as per test standard. Minimum life predicted is higher than the minimum life required as per testing
requirement. The sample is tested under standard testing procedure and observed that a sample meets the target life without failure.

Benefits Summary

1. Number of physical testing reduced, reduced cost of the proto building and testing.
2. Design evaluation time is reduced which in turn reduced the design cycle time and cost.
3. This study also contributes to a better understanding of system behavior and its structural strength.

Challenges

1. Simulation time for detailed model was drastically high, which enforced to compress the model size. Because of this, the small curvatures and fillets were neglected to avoid small element length. This helped to overcome small time step problem.

Future Plans

1. The same approach can also be extended to the analysis of fuel tank to avoid the fuel starvation and to improve the NVH performance.

Conclusions

The detailed analysis approach followed in this study will help the engineers to predict the performance of the fuel tank system and develop better structures with quick turnaround time. Fluid sloshing is having significant effect on the structure and vibration characteristics. It is possible to identify probable failure locations and work upon for design improvements. This study also contributes to a better understanding of system behavior and its structural strength for future projects applications.

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