Simulation of Fuel Sloshing – Comparative Study

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Abstract:

The paper outlines different approaches to fluid-structure interaction modelling in LS-DYNA. Different formulations (Lagrange, Euler, ALE and SPH) are evaluated and compared with experimental observations of a fluid sloshing problem in a simple container box. Computational simulations have shown that the motion of the fluid can be best described with the alternative methods in LS-DYNA. Additionally, such methods are very economical and suitable for analyses of large and more complex models.

Keywords:

Fuel sloshing, fluid-structure interaction, finite element method, computational methods, Lagrangian model, Eulerian model, ALE, SPH.

1 Introduction

In recent years numerical simulations have gathered on their importance and the recent trends are shifting from solving the individual problems to solving multi-physical problems by taking into account all the interacting systems. Detailed modelling of coupled problems is of crucial importance to assure the reliability of dynamic simulations.
The paper describes methods for simulating fluid-structure interaction with the LS-DYNA software system. Different formulations (Lagrange, Euler, ALE and SPH) for fluid simulation in LS-DYNA are presented and applied to a real fluid sloshing problem, with available experimental data.

2 Different formulations of system physical state description

Lagrangian formulation is usually used for describing a solid mechanics problem. The problem is described with a high number of mass particles, where the motion of every single particle is being observed in space and time. The problem is exactly defined when the motion of all the particles is known.
The Lagrangian formulation is very simple and easy to use for one or only a few mass particles. However, the method becomes very complicated and complex for description of high number of mass particles [3].
In the Eulerian formulation the problem is being observed at one point in space which does not follow the motion of the single particle. In one time step Δt several mass particles may pass the observed point. Their motion is exactly determined in the moment of passing through that point. In the observed point the field variables are time dependent.
The basic difference between the Lagrangian and the Eulerian formulation is that at the Lagrangian formulation the magnitudes *x*, *y* and *z* are variable coordinates of a moving particle. At the Eulerian formulation those coordinates represent steady coordinates of the defined field point [3].

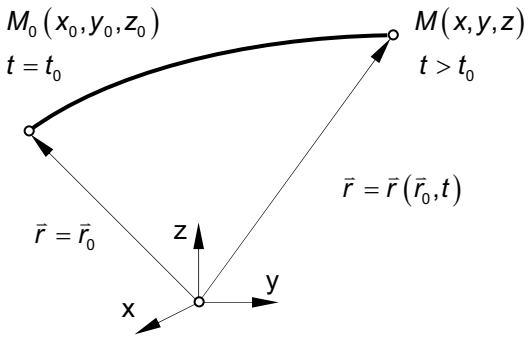

Figure 1: Lagrangian formulation

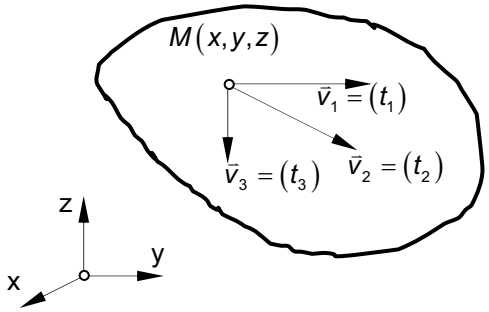

Figure 2: Eulerian formulation

3 Computational fluid dynamics methods in LS-DYNA

LS-DYNA is based on the finite element method and it was originally designed for solving structural dynamic problems. Its ability to model structural responses in general is well defined. However, the modelling of coupled problem of fluid-structure interaction is still quite challenging.

3.1 Lagrangian formulation

In the Lagrangian formulation one finite element represents the same part of the material throughout the course of the analysis. The fluid domain can be described with a material model which skips the calculation of deviatoric stresses. By defining a low bulk modulus for fluids such as water, the elastic shear forces become negligible, and by using a low yield stress, fast transition to plasticity can be achieved (e.g. by only considering the gravitation). Under high dynamic loading, the shear forces and any unreal introduced forces become negligible in comparison to the inertial forces of the fluid.
Figure 3 illustrates the solution process of a simple fluid problem using the Lagrangian formulation. It is presumed that the loading influences only the central node. The result of the loading is the shift of that node in a computational time step. If the influence of the loading does not stop or change, the node takes a new position in the next time step and the mesh deforms even more, since the mesh follows the material flow.

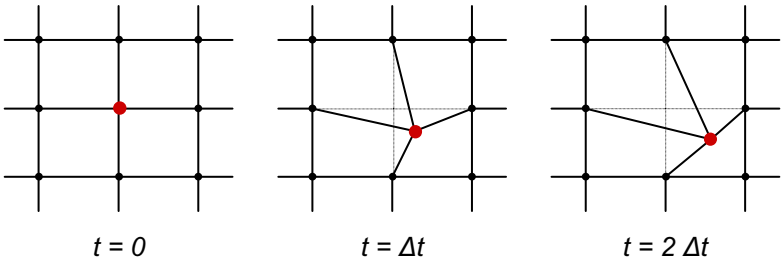

Figure 3: Solving a problem according to the Lagrangian formulation

3.2 Eulerian formulation

In LS-DYNA it is also possible to apply the Eulerian formulation for fluid flow analyses, where the fluid flow through the fixed mesh in a space is observed. The material point moves from one finite element to another and the finite element mesh does not move or deform. Although the Eulerian mesh in LS-DYNA appears not to move or deform during the analysis, it does actually change its position and form only within the single time step. The reason for this is the use of Lagrangian formulation in single time steps, which is much more advanced in LS-DYNA.
The Eulerian mesh in LS-DYNA is treated in a special way (Figure 4). To illustrate the use of an Eulerian mesh the same example is used as in the previous chapter. Because of the central node loading, the observed node changes its position during one computational time step (mesh deforms). After the time step the analysis stops and the following two approximations are performed:

- mesh smoothing: all the nodes of the Eulerian mesh, that have been displaced due to loading, are moved to their original position;
- advection: the internal variables (stresses, flow fields, velocity field) for all the nodes that have been moved are recomputed (interpolated) so that they have the same spatial distribution as before the mesh smoothing. In this way the mesh smoothing does not affect the internal variable distribution.

The described procedure is being repeated for each time step of the analysis and provides the analyst with a non-movable and undeformable Eulerian mesh.

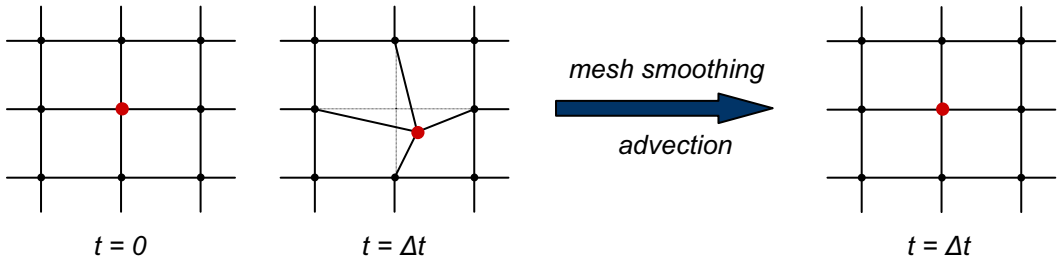

Figure 4: Solving a problem according to the Eulerian formulation

3.3 Arbitrary Lagrangian-Eulerian formulation (ALE)

In this formulation 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).

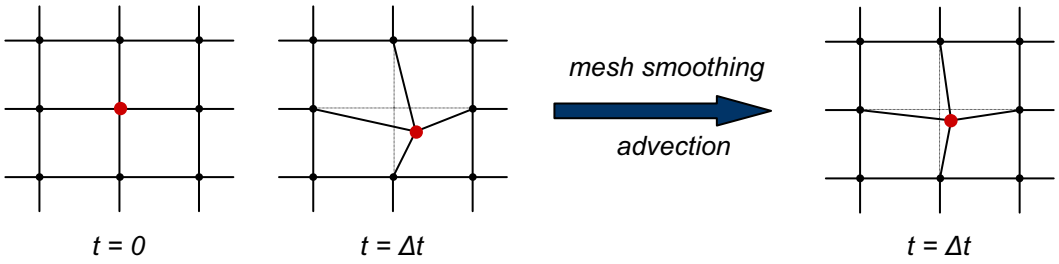

Figure 5: Solving a problem according to the Arbitrary Lagrange-Eulerian formulation

The ALE solving procedure is similar to Eulerian procedure. The only difference is the mesh smoothing. In the Eulerian formulation the nodes are moved back to their original positions, while in the ALE formulation the positions of the moved nodes are calculated according to the average distance to the neighbouring nodes (Figure 5).
A similar calculation scheme is also used in other comparable codes (i.e. MSC/Dytran).
In LS-DYNA there are two types of ALE elements: single material and multi material. Single material element type can contain only one phase (fluid) at one moment, while the multi material element type is able to contain several materials.
The advantage of the ALE formulation is evident when a stress front needs to be followed and the mesh is automatically refined. Another example is analysis of fluid tanks, where fluid movement inside the tank is of interest and the boundary surface is continuously changing due to interaction between fluid and tank surfaces (Figure 6).

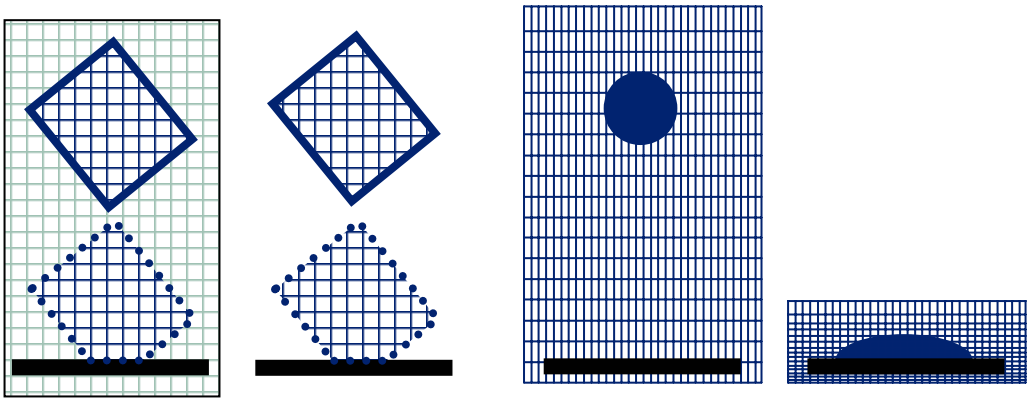

Figure 6: Applications of the ALE mesh

3.4 Smoothed Particle Hydrodynamics (SPH)

The SPH method is an integration scheme which was developed by Lucy, Gingold and Monaghan (1977). It is based on the Lagrangian formulation with the purpose to avoid the mesh restrictions when lare deformations appear within the finite element method. The main difference between the standard methods and the SPH is the absence of the mesh, since the SPH formulation is essentially a meshless method (Figure 7).

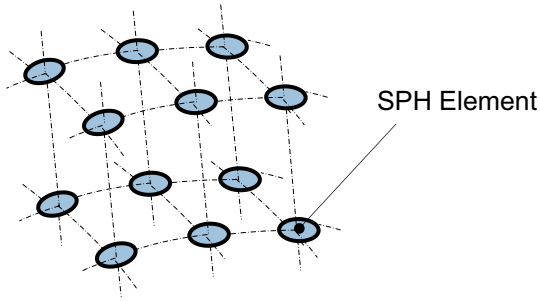

Figure 7: SPH model

4 Comparative study of different approaches for solving a practical example

4.1 Problem description and computational model

The analysed problem consists of a closed container box at rest, 60% filled with water and 40% with air (Figure 8), which is subjected to longitudinal time-dependent acceleration with a peak acceleration of approx. 30 *g* at time t = 40 ms. The time dependent variation of the water surface shape and water pressure at point 1 was previously measured in experimental testing of the box made of PMMA plates with 30 mm thickness [5]. The box was attached to a sled (fixed in vertical direction) and accelerated with an acceleration-time function *a*. The initial velocity of the model at the time t_0 = 0 s is 0 m/s.

The box was modelled with four-noded Belytschko-Tsay shell elements with three integration points through the thickness. The elastic material model is used for the box container with material data corresponding to the PMMA material (ρ = 1180 kg/m^3, E = 3000 MPa and ν= 0,35). Only the bottom surface of the box was modelled as rigid. For the water and air solid and SPH elements were used, depending on the applied method. The material model Null (Type 9) was used for water (ρ = 1000 kg/m^3 at 293 K) and air (ρ = 1 kg/m^3 at 293 K) modelling. The Air was considered only in Eulerian and ALE model. The Gruneisen (Water and Air) and Ideal Gas (only for Air) equations of states have been used. The model was also loaded with the constant gravitational acceleration (g = 9,81 m/s^2). In the Lagrangian and SPH model the automatic nodes to surface contact were used and in the Eulerian and ALE model the contact between fluid and structure was defined with the keyword Constrained Lagrange in Solid.

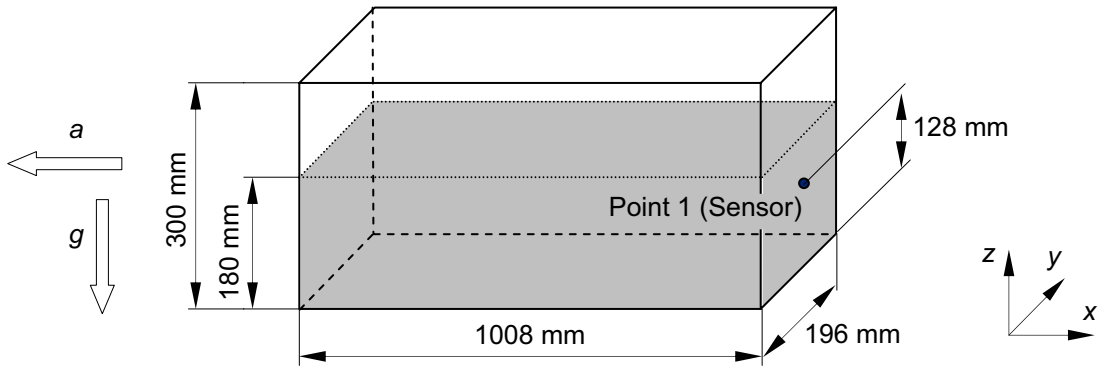

Figure 8: Dimensions and initial conditions of the Plexiglas box

For comparison between the computational and experimental results, the experimentally observed free surface shape at t = 38 ms was considered.

4.2 Computational analyses data

Explicit dynamic analyses were carried out by using all four different fluid model approaches: Lagrangian, Eulerian, ALE and SPH. The models have been solved with LS-DYNA Linux Version 970. The computational time frame was set to 80 ms and the time step of the simulation was defined according to the lowest resonant frequency of the structure and was set to 0,01 ms.

4.3 Computational results

The free surface shape prediction results of all four dynamic simulations at the time of t = 38 ms are represented in Figures 9 to 12. The dotted line in all figures represents the free surface shape observed in the experiment at the same time instance.

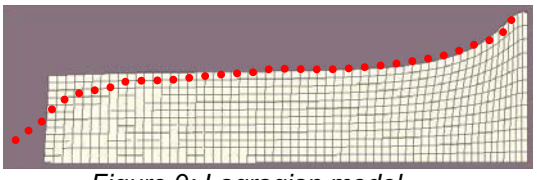

Figure 9: Lagragian model

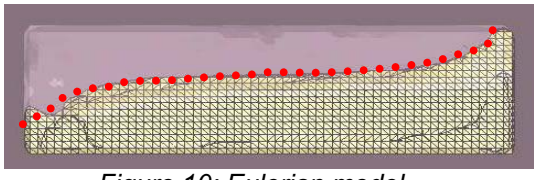

Figure 10: Eulerian model

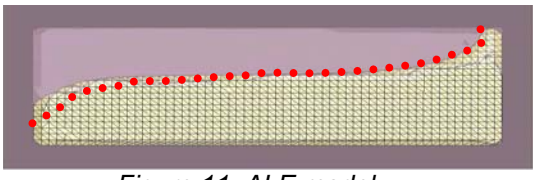

Figure 11: ALE model

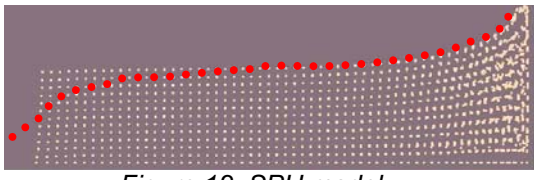

Figure 12: SPH model

From Figures 9 and 12 it is obvious that the Lagrangian and SPH models are only good for approximations of the fluid motion at the right side wall, since in reality the fluid would not retain the form of the container, which is the case observed in simulations at the left side wall. However, this

observation must be considered in view of required computational results. In case where only the impulse of the fluid towards the tank wall is needed, the deformations and deflections on the opposite side could be neglected. Eulerian and ALE formulations are performing much better in describing the position and form of the water free surface. However, this is only achieved by dramatic increase of calculation times, which is not always acceptable. Figure 13 represents the fluid motion in a box during the calculation time. It is important to observe that by using the Lagrangian formulation results in very distorted elements and consequently large computational errors. This again confirms the fact that the Lagrangian formulation is unsuitable for large deformations.

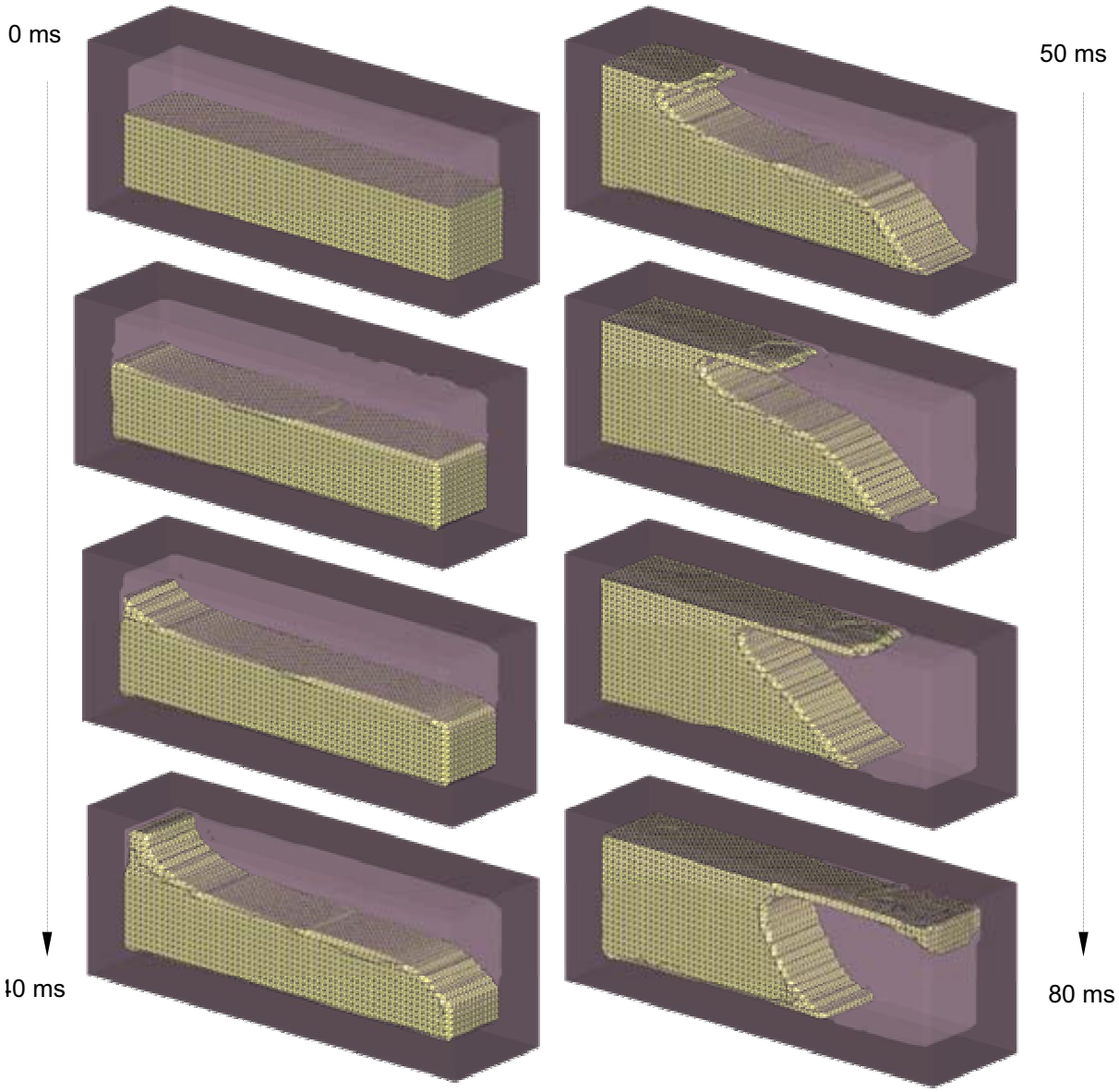

Figure 13: Fluid motion modelled with ALE formulation

The time variation of water pressure at point 1 is shown in Figure 14. The results have been determined by two different approaches. In the Lagrangian and SPH model the pressure at point 1 was measured with contact forces which appeared at the observed point. For the Eulerian and ALE model the pressure was determined by the leakage control, i.e. by determining the force that is needed for establishing equilibrium in every observed element on the boundary between the fluid and the box wall.

The best agreement with the experimental results was achieved by using the Lagrangian and ALE formulations. The SPH formulation also provided good results, especially when taking into account that modelling analysis by using this formulation is very quick and uncomplicated (the mesh consists only of SPH nodes – elements). The drop of the pressure, observed by Eulerian formulation, is

attributed to the need for a different air model (a different equation of state), which is necessary to assure a stable analysis.

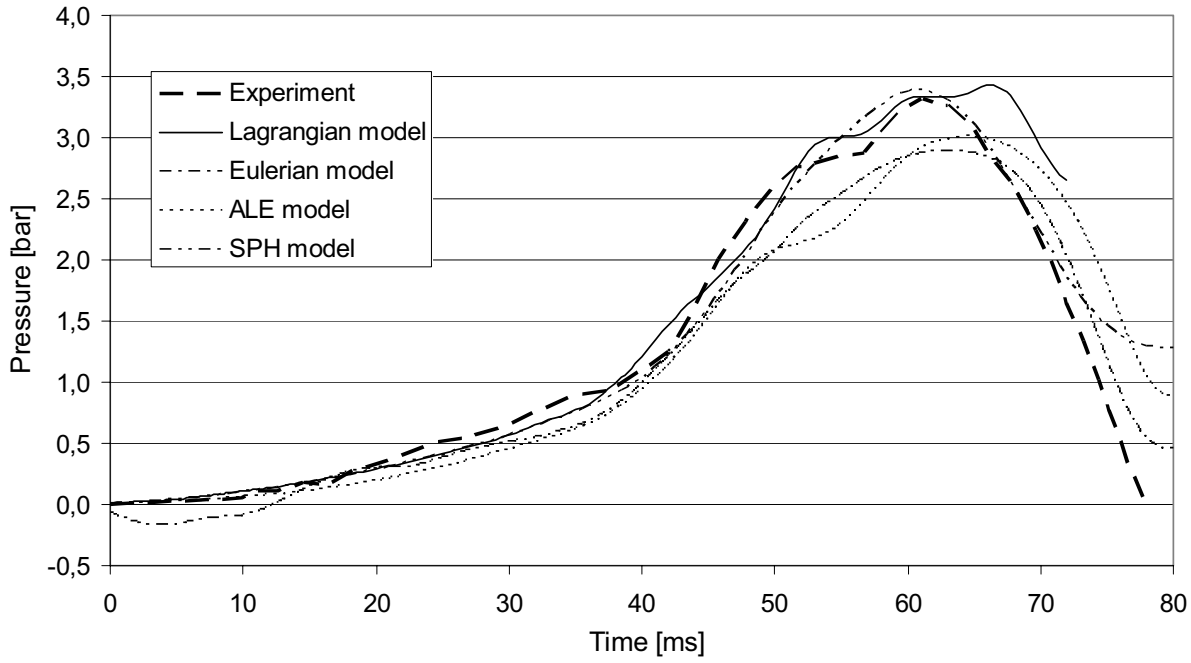

Figure 14: Comparison of the pressure time-variation at point 1

The model size and required CPU times for each analysis are listed Table 1 in order to illustrate the required computational effort for solving the chosen problem with different approaches.

Table 1: CPU-time comparison

Model	**Total number**		**Time frame** [ms]	**CPU time** [min]
	Nodes	**Elements**		
Lagrange	2898	2420	80	16
Euler	10162	8706	80	225
ALE	7462	6396	80	260
SPH	2898	2896	80	13

The deformation of the box container is negligible, which is due to a large thickness of the box walls. To clearly illustrate the fluid-structure interaction capabilities of LS-DYNA, another analyses were carried out where the container box walls had only 10% of the original thickness, i.e. 3 mm [6]. The resulting deformations of the container box due to fluid-structure interaction can be observed in Figure 15.
Following from the reported simulations is obvious that these approaches offer an alternative means of fluid flow modelling and its interaction with the structure. Advantage of using the SPH and Lagrangian model is short pre-processing and reasonable computational time, while the ALE and Eulerian models can describe the fluid motion more accurately. Nonetheless, the initial impact of the fluid on the box wall could be simulated accurately with all four fluid models incorporated in LS-DYNA.

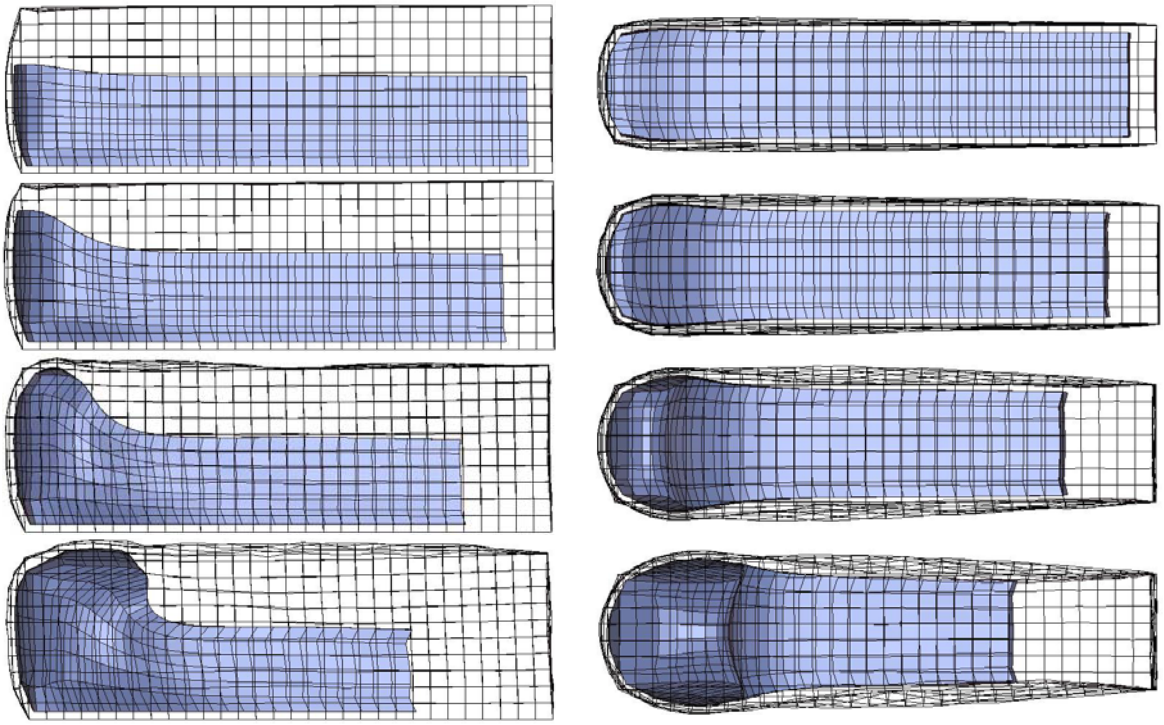

Figure 15: Fluid-structure interaction.

5 Conclusion

Four approaches to fluid flow modelling in LS-DYNA have been presented in the paper. Different formulations (Lagrangian, Eulerian, ALE and SPH) have been used to analyse a fluid motion in deformable box, with the purpose to validate the results in comparison with existing experimental observations. Computational simulations have shown that the fluid motion and fluid-structure interaction can be accurately described by applying different alternative formulations in the LS-DYNA. The applied models provide a basis for economical computational models that can be used for analysing more complex problems (e.g. automotive fuel tanks).

6 References

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