SPH-Based Fluid-Structure Interaction to Aid Rapid Prototyping for Vehicle Water Wading

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Numerical simulation has become a key design tool in the automotive industry. While Computational Fluid Dynamics (CFD) evaluates aerodynamic and hydrodynamic aspects, Computational Structural Mechanics (CSM) focuses on structural integrity. Typically, these aspects are considered separately, but under certain conditions, the interaction between fluids and structures, also known as Fluid-Structure Interaction (FSI), becomes strongly coupled and too complex for independent assessment.

In deep water wading, a vehicle entering water at high speed experiences significant hydrodynamic loads, potentially causing excessive deformations or structural failure of components. Adding to the complexity, suspension systems have a large impact on vehicle dynamics during water wading. Therefore, capturing the interplay between these highly dynamic aspects of the complete vehicle system during wading scenarios is essential for accurate load predictions needed for optimal design.

The coupled nature of such FSI phenomena can be challenging to analyze numerically since the fluid and structural problems and their interaction are to be considered simultaneously. Typically a partitioned framework is employed to solve the individual problems in a coupling loop for each timestep until convergence is reached. On top of that an additional vehicle suspension model is needed to incorporate the dynamics of the suspension system.

Even though a partitioned approach allows for the coupling of arbitrary CFD and CSM solvers, it comes several drawbacks, such as the large number of coupling iterations often required for convergence [1]. Furthermore, non-conforming meshes at the fluid-structure interface require additional measures for an energy-conserving and consistent interface coupling.

A mesh-free approach recently made available within PreonLab solves the fluid and structural problems in a coupled sense for each time step using a full Smoothed-Particle Hydrodynamics (SPH) formulation. The particle based FSI approach omits the need for coupling iterations as well as any special treatment of non-compatible interface discretizations. Furthermore, it leverages the inherent advantages of SPH methods, such as handling large deformations and topology changes naturally. Moreover, PreonLab provides a car suspension model to simulate the suspension system for every individual wheel and the dynamics of the entire vehicle.

This work demonstrates the capabilities of the particle-based method in the context of FSI in automotive applications. First, the method is validated using common yet challenging FSI benchmark problem. Second, the method is applied to a deep-water wading scenario in which underbody panel deformations are investigated. The latter focuses on demonstrating how numerical analysis of FSI phenomena integrates into rapid prototyping workflows commonly used in the car industry.

I. MATERIAL AND METHODS

In the presented work, the commercial software PreonLab [2] is used to model FSI phenomena. PreonLab is equipped with the Implicit Incompressible SPH (IISPH) approach to solve fluid flow problems. IISPH incorporates implicit time integration by solving the pressure Poisson equation to couple velocity and pressure fields for the incompressible flow condition. This allows for significantly larger time steps as compared to the Weekly Compressible SPH (WCSPH) approach, where the artificial speed of sound is often a limiting factor for the maximum allowable timestep. As stated in [3], IISPH requires fewer steps to converge in comparison to Implicit SPH (ISPH). Furthermore, fluid interaction with rigid walls is modeled by a modified version of the method proposed in [4], which utilizes a single layer of particles to sample solid surfaces. This allows for lower memory overhead as compared to ghost wall particle-based approaches while accurately capturing sharp geometric details.

In addition to the IISPH approach for fluid flow problems, an implicit formulation is used to model incompressible linear elastic materials. One of the challenges of solving such materials using SPH is the handling of rotations. This is due to the fact that common SPH kernel gradient interpolation is not first-order consistent. As a result, rotations are misinterpreted as deformations, and the elastic forces are not rotationally invariant. PreonLab uses the formulation proposed in [5] which solves this issue by applying a correction to the kernel gradient and employing a corotated deformation gradient. This approach leads to a linear formulation that can be solved efficiently with implicit time integration. Similarly to IISPH, the implicit formulation allows for larger timesteps and therefore computationally efficient simulations compared to explicit formulations.

The elastic problem is solved within the IISPH framework of the fluid problem. The interaction at the fluid-structure interface is handled implicitly by accounting for the relevant forces, such as those induced by friction and pressure. The Lagrangian nature of the SPH formulation naturally accounts for the deforming structure. Hence, no additional update steps for deforming geometries are needed, as is typical for mesh-based FSI methods.

II. RESULTS AND DISCUSSION

The presented FSI framework is validated with benchmark problems, including a sloshing tank with free surfaces and a deep-water wading scenario involving vehicle underbody panel deformations. The aim of the latter case is to demonstrate how the presented method can be applied as a tool to aid rapid prototyping of vehicle components.

A. Sloshing Tank With Flexible Baffle

Tank sloshing is a highly dynamic phenomenon that occurs in fuel tanks that are partially filled. The dynamic behavior of the fluid can lead to undesired excessive pressure loads on the tank walls. Baffled structures are typically placed inside the tanks to break up the fluid volume into smaller partitions. By doing so, the baffles reduce the build-up of momentum by the fluid and consequently reduce impact loads on the tank walls. A secondary function of the baffles is to add structural stiffness to the tank walls.

To demonstrate the performance of the solver in the context of sloshing tanks, a simplified FSI benchmark is studied next. This particular case was introduced in [6] and considers the sloshing behavior of a partially filled tank that contains an elastic beam at its center (see Figure 1). The applied material properties are identical to those used in [6]. The sloshing behavior of the fluid is achieved by rotating the tank with a rotation angle varying sinusoidally between $\varphi \in [-4.0, 4.0]$ degrees. The metric considered in this study is the horizontal tip deflection of the elastic beam induced by fluid loads.

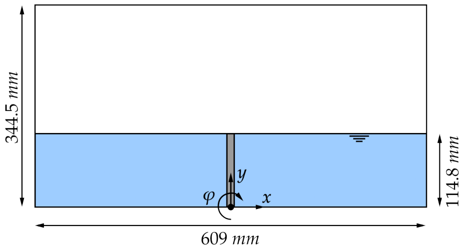

Fig. 1: Problem setup for sloshing tank.

The sloshing tank is simulated in 2D using a particle spacing of 1.0mm and 0.5mm for the fluid and beam, respectively. A snapshot of the deflected beam and the fluid inside the tank at $t = 1.84s$ is shown in Figure 2. In this figure, the deflection of the beam is clearly visible. The effect of the beam on the free surface can also be observed. The time history of the tip deflection of the beam itself is given in Figure 3 for four oscillation cycles.

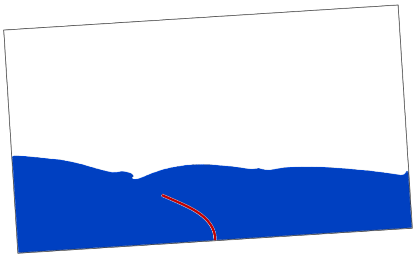

Fig. 2: Deflecting beam in sloshing tank at $t = 1.84s$.

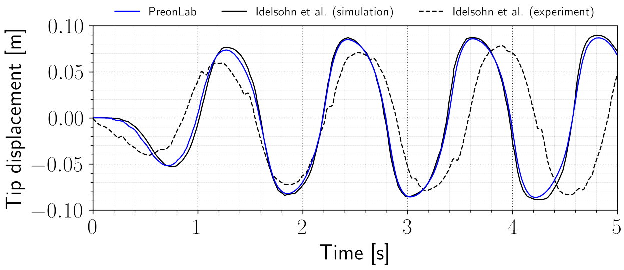

Fig. 3: Horizontal tip deflection of the elastic beam. Reference data taken from [6].

As can be observed from this graph, the resulting tip deflection closely matches the numerical reference data from [6]. Similar to the reference, larger deviations are observed when comparing with experimental measurements, which can be attributed to slight differences in setup, 3D effects, as well as uncertainties in the measurements. Based on the presented data, the FSI solver framework shows itself to be a suitable tool for the analysis of tank sloshing phenomena.

Moreover, the presented benchmark problem contains free surfaces and moving domains, which typically need special treatment in mesh-based methods such as interface capturing or tracking. The provided numerical results demonstrate that the advantages of SPH in this regard also hold for the presented coupled FSI framework.

B. Underbody panel deformation in deep water wading

Up to this point, the performance of the FSI solver framework has been demonstrated in the context of large rotations and free surface interactions. In the following case, the framework is applied to a real-world automotive application. More specifically, we demonstrate how the method can be used as a tool to quantify the dynamic response of an elastic underbody panel subjected to hydrodynamic loads during a deep water wading scenario. The complexities of free surface flows and large translations of the previous benchmark problem are combined in this testcase.

As depicted in Figure 4, the problem is focusing on the elastic response of an underbody panel of a vehicle entering a water wading channel with a depth of 300 mm. The panel is located directly under the engine bay of the vehicle and is supported at the locations shown in Figure 5. To showcase the importance of support mount placement, two variants shown in Figure 5 are compared, i.e., a setup with only the supports depicted in green and one setup with an additional support placed at the circle marked in red. The additional support at the center is placed in the region where large deformations are to be expected.

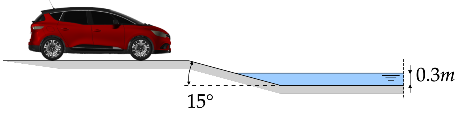

Fig. 4: Problem setup for wading simulation.

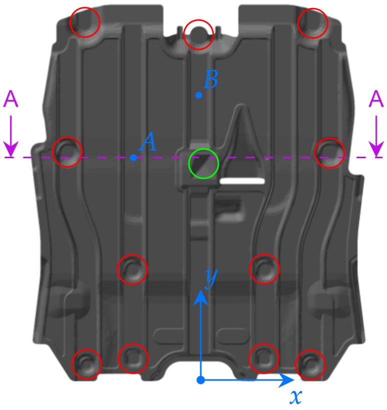

Fig. 5: Top view of the panel. Red circles indicate mounting point locations of the panel. An additional mounting point is placed at the center of the panel and marked in green.

The vehicle enters the wading channel at $15\mathrm{km/h}$. For the elastic panel, standard Polyethylene Terephthalate (PET) material properties are applied. The computational domain is discretized using multi-resolution particle spacing between 2 and $64\ \mathrm{mm}$ for the fluid and a uniform spacing of $0.8\mathrm{mm}$ for the elastic panel. To compare the different panel support designs, the panel deflections at point A and B depicted in Figure 5 are measured.

Figure 6 shows the vertical panel deformation at A and B over time as the vehicle enters the wading channel. The location of these points are chosen to be in the center between the additional support and its direct neighbors in order properly highlight the effect of the additional support (see fig. 5). At locations A and B, panel deformations can be observed for both of the panel mount setups. As expected, the panel deflections at point B is significantly reduced due to the additional mounting point. The additional mounting point, however, results in a slightly increased panel deformation at measuring point A. To further highlight the difference between the two setups, a cross section is given in Figure 7. From this figure it is clear that the added mounting point reduced the overall panel deflection even though there is a slight increase in the local deformation at point A.

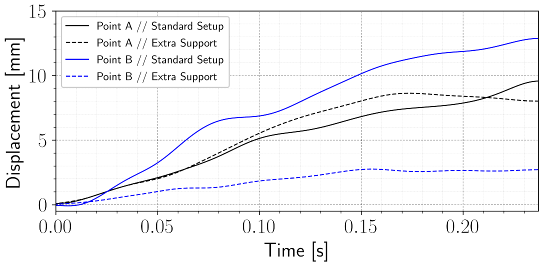

Fig. 6: Panel deflection at point A and B for different mounting designs.

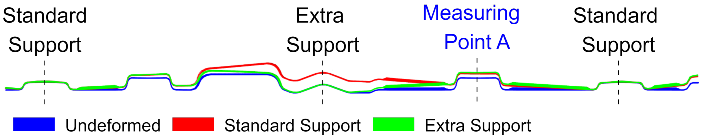

Fig. 7: A-A cross section from fig. 5 at $t = 0.125\mathrm{s}$ after the water reaches the panel.

III. CONCLUSION

The provided examples illustrate the potential of a fully particle-based FSI solver framework for rapid prototyping in the automotive industry. The general performance of the method is validated through the sloshing tank benchmark case, demonstrating strong agreement with both numerical and experimental reference data. Moreover, the applicability of this framework as a practical tool for vehicle design is highlighted through the study of underbody panel deformations during a deep-water wading scenario. Simulations of two panel mounting support setups were conducted, and the resulting elastic responses were compared. Despite the lack of experimental reference data, the observed panel deformations meet expectations and offer valuable insights.

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