Design of a Generic Chrono Framework for Fluid-Solid Interaction

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I. Introduction

Fluid-Solid Interaction (FSI) problems are ubiquitous. We are particularly interested in interactions of rigid and flexible multibody system with fluid phase (more than fluid-structure interaction problems). Examples of relevant applications include vehicle mobility (fording operations, liquid sloshing in tanks, vehicle interaction with deformable terrain) and offshore energy applications (wave and tidal energy converters, offshore wind, etc.). Chrono [1] has provided FSI support for a long time, through its Chrono::FSI module which implements a CUDA-based fluid solver based on the Smoothed Particle Method (SPH) [2]. An important feature of the Chrono::FSI module is that it provides support for solving both Navier-Stokes equations for incompressible CFD, as well as solving continuity and momentum equations describing homogenized granular dynamics, referred here as Continuous Representation Method (CRM), used to model deformable soil. Recent interest in Offshore Energy Systems (OES) has motivated a refactoring and redesign of Chrono::FSI aiming at: (i) separating the interface between Chrono multibody system solver and a fluid (hydrodynamics) solver; (ii) redesigning the Chrono SPH solver to seamlessly support different continuous equations of motion (CFD and CRM); (iii) enhancing accuracy, robustness, and performance of the Chrono SPH solver; (iv) extending the SPH-based FSI interface to improve its modeling, visualization, and post-processing capabilities.

This contribution describes the structure of the new Chrono::FSI generic interface between a Chrono solid-phase multibody system and an arbitrary fluid solver, as well as the integration of the existing SPH fluid solver in this framework. We provide a summary of new developments and enhancements of the Chrono SPH solver, both for CFD and CRM problems and integration with the Chrono co-simulation framework. We conclude with an example of a marine wave energy-harvesting device.

II. Chrono::FSI design

The high-level organization of the redesign Chrono::FSI module is illustrated in Fig. 1 and is centered around an abstract FSI system (`ChFsiSystem`) which holds references to an (externally-provided) Chrono multibody system, an arbitrary fluid solver system, and an abstract coupling interface which intermediates the data exchange between phases. Fig. 1 includes the current Chrono SPH solver as an instance of a concrete fluid solver which can be incorporated in this framework. Current plans provision for extending the suite of hydrodynamics codes integrated to Chrono::FSI to include the HydroChrono [3] potential flow solver and potentially other solvers (e.,g. DualSPhysics, OpenFOAM).

The generic `ChFsiInterface` defines the solid phase through its collision geometry (thus consistent with solid-solid contact representation in Chrono) and implements data exchange using fluid solver-agnostic data structures. In particular, rigid bodies are described as a collection of collision shapes (primitives or triangular meshes) with associated transforms relative to the body reference frame, while deformable solids are described by associated collision surfaces (which can be a segment set for beam-like elements or surface meshes for shell and solid finite elements). Among other things, this allows use of arbitrary finite elements.

The FSI problem is solved in an explicit force-displacement co-simulation setting, with the Chrono system communicating full state information of the solid phase (position and velocity level) and the fluid solver sending fluid forces and torques acting on rigid bodies or on nodes of the FEA meshes. `ChFsiSystem` controls the co-simulation time stepping function, first invoking the data exchange functions through `ChFsiInterface` then advancing the dynamics of the two phases simultaneously and in parallel (using non-blocking concurrent threads).

III. SPH developments

Concurrent with the redesign of the Chrono::FSI infrastructure, we have refactored the current SPH solver to (i) address accuracy, robustness, and flexibility; (ii) improve computational efficiency; and (iii) enhance usability and ease of modeling complex scenarios. Among the new features added to the Chrono SPH solver, we mention: optional use of the δ-SPH formulation, more options for kernel specifications, different option for the equation of state in Weakly Compressible SPH (Tait and isothermal), different options for viscosity treatment (including both laminar and artificial), and different options for formulating boundary conditions (Adami and Holmes).

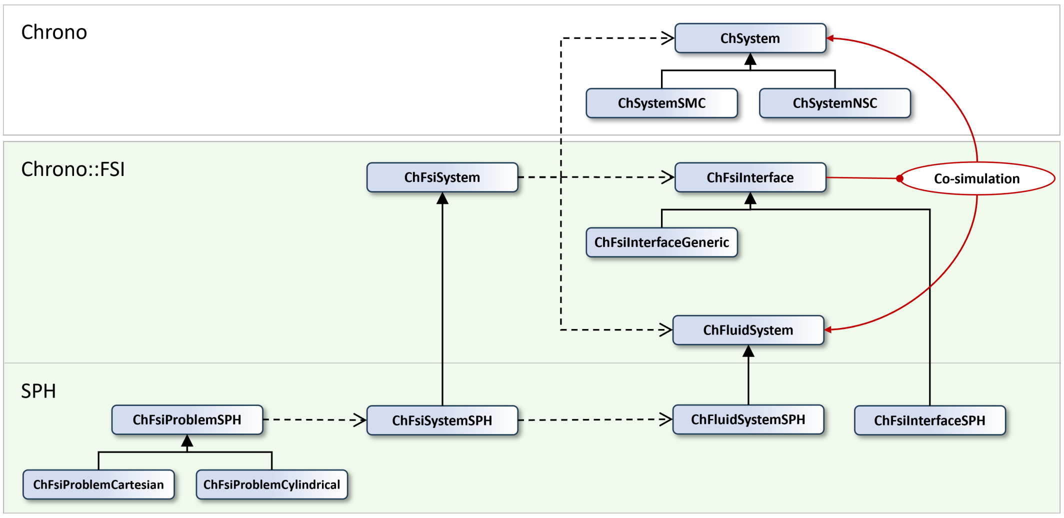


Fig. 1: Class diagram of the Chrono::FSI module

To improve performance, the proximity search was optimized to construct persistent neighbor lists and allow for user-controlled over their update frequency. A second efficiency improvement comes from using GPU shared memory during the accumulation of fluid forces on solids (rigid bodies or FEA nodes) which led to a significant reduction of the required atomic operations.

Finally, for improved code usability, we introduce a high-level class (`ChFsiProblemSPH`) which (i) supports both CFD and CRM problems, (ii) supports problem definition in either Cartesian or cylindrical coordinates, (iii) allows setting up problems with solids initially embedded in the fluid phase, (iv) automatically defines wall boundary conditions, and (v) provides utilities for creating various test environments (e.g., wave tanks).

We illustrate capabilities of the FSI framework using an application in offshore wave energy converter (WEC) system.

IV. Case Study: WEC System

One method of harvesting wave energy involves using a Variable Geometry Wave Energy Converter (VGWEC). These devices can adapt to varying wave conditions by adjusting their geometry to maximize energy captured while reducing structural loads. For instance, the device introduced in [4] utilizes four adjustable mini-windows that open and close at specific angles, as shown in Fig. 2. The device is placed at approximately one wavelength from a piston-driven wave maker, which generates sinusoidal waves. At the far end of the tank, a sloped beach is placed for dissipating reflective waves. The device is hinged to the tank floor with a revolute joint, enabling it to rotate in response to incoming waves. At the joint, a torsional spring-damper mechanism is utilized to model the Power Take-Off (PTO) setup, with a stiffness $k = 6.57\,\mathrm{N\,m}$ and a damping coefficient $c_{PTO} = 0.5\,\mathrm{N\,m\,s}$. The SPH solver parameters are outlined in Table I. Approximately 700 000 SPH markers were generated. A Real Time Factor of 720 seconds per simulated second is achieved with an NVIDIA RTX 4070Ti GPU.

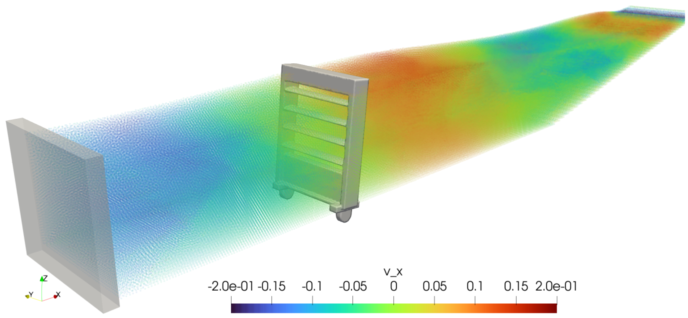
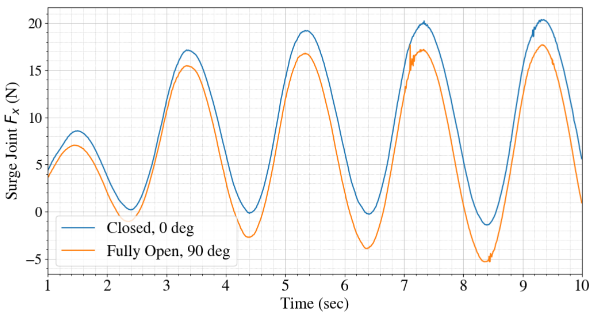


Fig. 2: Snapshot from a WEC simulation in a wave tank with dimensions $5\,\mathrm{m} \times 5\,\mathrm{m} \times 0.5\,\mathrm{m}$, showing the device with its mini-windows fully open. The wave tank boundaries are not visualized.

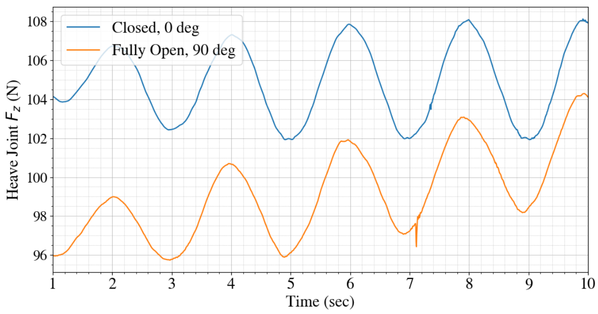
TABLE I: SPH Solver Parameters (all units in SI).

Parameter	**Value**
initial spacing Δx	0.01
kernel type	Wendland
d_0 multiplier	1.2
maximum velocity	4
boundary type	ADAMI
artificial viscosity α	0.02
density diffusion δ_ϕ	0.1
step size Δt	2.5×10^{-5}

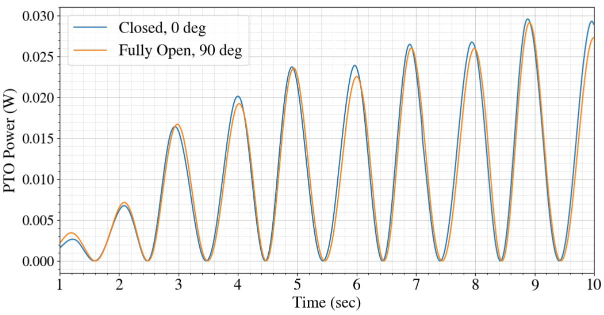
We compare the performance of two flap geometries: one with mini-windows fully open and the other fully closed. Figure 3 presents the time-series results of the joint forces in the surge (F_x) and heave (F_z) directions, as well as the power extracted by the PTO mechanism, evaluated using $P(t) = c_{PTO}\dot{\theta}^2$, where $\dot{\theta}$ is the pitch angular velocity of the flap. The results indicate



(a) Surge force F_x at the joint over time.



(b) Heave force F_z at the joint over time.



(c) Power extracted over time from the PTO mechanism.

Fig. 3: Time-series analysis of forces at the joint and power extraction.

that the closed configuration experiences significantly higher forces at the joint compared to the open one. As shown in Fig. 3a, the surge force F_x oscillates with greater amplitude in the fully closed setup due to increased hydrodynamic resistance. Similarly, Fig. 3b shows that the heave force F_z has a higher mean value in the fully closed configuration. For the energy extraction, the closed configuration achieves slightly higher peaks in PTO power, as shown in Fig. 3c. Overall, the fully closed configuration demonstrates higher peak power but at the cost of increased joint loads, while the fully open configuration can reduce joint loads. These results highlight the advantages of VGWEC, where the flap angle can be adjusted to optimize energy extraction while minimizing structural loads.

V. Conclusion and Future Work

This work utilized the Chrono::FSI framework to simulate fluid-solid interaction for a wave energy converter (WEC) system. The modular design of Chrono::FSI, with its decoupled solid and fluid solvers, provides a versatile platform for simulating complex multiphysics problems. The case study demonstrated the performance of a VGWEC design with two different configurations. Future work will further analyze the performance of the VGWEC across a range of wave conditions and opening angles. Additionally, ongoing improvements to Chrono::FSI will focus on enhancing modularity, performance, and compatibility with other solvers to support more advanced fluid-solid interaction studies.

Acknowledgments

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