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An efficient finite-volume method to study the interaction of two-phase fluid flows with elastic structures

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HIGHLIGHTS

- We have presented a fluid–structure interaction procedure for two-phase flows based on the finite volume method.
- The integration of this procedure on a multi-region simulation framework allows for real parallel FSI simulations.
- We validated this procedure and conducted accurate and efficient FSI simulations characteristic of wave impacts.

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ABSTRACT

We introduce a fluid–structure interaction (FSI) framework for the resolution of two-phase fluid flow problems and isothermal non-linear elastic bodies. The discretisation of both the fluid and solid governing equations relies exclusively on the finite volume method. A strong coupling partitioned approach is implemented to ensure the two-way coupling of information between the fluid and solid regions defined in the simulation. Moreover, this FSI framework is integrated on top of a multi-region coupling procedure developed in companion papers [Martínez-Ferrer et al. (2016, 2018)], which has been successfully applied in numerical wave tanks (NWTs), and shown to work transparently with standard domain decomposition techniques used in parallel simulations. Therefore, this retained approach results in a high performance computing strategy to carry out accurate and efficient FSI simulations of wave impacts against structures characteristic of ocean and coastal engineering problems.

We conduct a series of test cases to verify the implementation of this FSI framework and its parallel performance for an increasing number of CPU cores. These benchmarks include the dynamic and static responses of cantilever and clamped beams under various loads, a lid-driven flow in an elastic cavity, the water entry of an elastic wedge and, finally, a water dam impact on an elastic plate. The results obtained in this work agree well with analytical solutions, laboratory measurements as well as other numerical simulations reported in the literature.

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1. Introduction

The interaction between two-phase fluid flows, e.g. waves, and structures is a complex problem that is gaining attention from the academic and industrial sectors due to its importance in offshore renewables worldwide.[1,2] The harsh operating conditions, e.g. corrosion from exposure to seawater, high wind and wave loads, etc. to which these new energy systems are exposed can have a dramatic impact on both their survivability and long-term reliability. This is extremely important for offshore devices whose remote location requires helicopters and boats to carry out maintenance or even full replacement after stormy weather. Therefore, such systems must be designed more robustly in order to reduce their associated high maintenance costs. For this purpose, analysis and modelling tools can help by improving the performance and reliability of these devices so they can effectively contribute to the world energy production.

As the seas are often a hostile environment, the ability to model and predict waves loads is crucial for energy systems and compliant structures in ocean and offshore engineering such as catenary-moored floating vessels, articulated columns, guyed towers, tension leg platforms, etc. On the one hand, numerous experiments (Lugni et al., 2006; Bullock et al., 2007) and simulations (Bredmose et al., 2009; Ma et al., 2015) of waves impacting against rigid structures have already demonstrated that air pockets trapped in water bodies can be subject to expansion and compression by the surrounding liquid. As a result, such impacts can yield stronger peak pressures on the structure followed by pressure oscillations above and below atmospheric pressure. Although the aforementioned works do no take into account hydroelasticity effects, i.e. the structure is considered a solid rigid body, they offer valuable insight into how such pulsating loads can contribute to accelerating the ageing of offshore structures or even damage them permanently. On the other hand, hydroelastic effects produced by the impact of water bodies on simple geometries, e.g. wedges and plates, have been studied in the literature (Cappelli et al., 1968; Zhao and Faltinsen, 1993) to determine their dynamic structural response. A recent experiment (Lugni et al., 2014) carried out in both fully rigid and elastic sloshing wave tanks has found three different hydroelastic regimes during slamming. The first regime corresponds to a quasi-static deformation of the beam and the third regime is characterised by a free-vibration of the beam. During the second regime, a strong and fully coupled hydroelastic behaviour produces a rapid pressure increase that originates the maximum strain. As a consequence of the structural reaction and bending inwards, the hydrodynamic load further increases in comparison to the fully rigid experiment, which can compromise the integrity of the structure if a certain strain threshold is exceeded. The same authors found similar results using simplified theoretical models and numerical simulations (Lugni et al., 2014). Therefore, it seems that the solid rigid assumption is not always appropriate for the accurate modelling of waves interacting with structures and thus more complex *flexible* fluid–structure interaction models should be employed.

From a numerical modelling point of view, the interaction between a flexible structure and its surrounding environment, e.g. waves and wind, can be decomposed into two main parts: (i) the modelling of the fluid medium with the aid of computational fluid dynamics (CFD) and (ii) the analysis of the structural response to its environment with the aid of computational structural mechanics (CSM). There is a wide variety of CFD methods for the resolution of free-surface flows. The finite volume method (FVM) remains the most popular, see for instance Rusche (2002) and Ma et al. (2014), although numerous examples can be found in the literature using the boundary element method (BEM) (Zhao and Faltinsen, 1993) or the smoothed particle hydrodynamics (SPH) method (Vignjevic and Campbell, 2009; Guilcher et al., 2010) to mention but a few. For the resolution of CSM problems, the finite element method (FEM) is widely established in both academia and industry (Zienkiewicz and Taylor, 1990; Bathe et al., 2001). To a much smaller extent, one can also find works that have demonstrated the capacity of the FVM to solve structural problems with large deformations (Jasak and Weller, 2000; Slone et al., 2003).

FSI simulations do require the coupling of CFD and CSM tools (Hou et al., 2012) and are commonly employed in ocean engineering problems (Robertson et al., 2014). FSI is part of a wide range of multi-physics problems involving different physical phenomena (Keyes et al., 2013) such as fluid dynamics, solid mechanics, thermodynamics, radiation, magnetism, etc. Multi-physics simulations are rather complex and depend on the physical laws as well as the relevant time and spatial scales and therefore represent a challenging area for future research (Brown et al., 2008). In the particular case of FSI simulations, there are several strategies for the coupling of CFD and CSM tools: some of them rely exclusively on the FEM (Donea et al., 1982; Taylor et al., 1998) or the FVM (Slone et al., 2004; Tukovic and Jasak, 2007) for both the resolution of the fluid and solid equations. However, the most popular methodology, and the one that has been widely adopted by the industry, consists of combining CFD software (typically based on the FVM) and CSM software (relying on the FEM) with a third-party multi-physics coupling manager (Aksenov et al., 2004; Aagaard, 2013; Ali et al., 2017) that often controls the data exchange between them through the computer file system (I/O level operations). Nevertheless, with the increasing demand on heterogeneous and high performance computing (HPC), most of these FSI strategies are no longer competitive due to their lack of support for parallel computing. For this reason, having the fluid and solid solvers integrated in the same executable code and using a parallel programming model yields efficient FSI simulations (Lv et al., 2006). An efficient implementation for FSI can also be achieved via multi-region coupling (Martínez-Ferrer et al., 2016, 2018), which also offers the advantage of being completely transparent to parallel algorithms. Multi-region coupling applied to numerical wave tanks

[1] The Catapult Programme: Offshore Renewables Opportunity (https://ore.catapult.org.uk/).

[2] News article "China makes a big bet on offshore wind, Renewable Energy World" (http://www.renewableenergyworld.com/articles/2017/10/china-makes-a-big-bet-on-offshore-wind.html).

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