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Enhanced particle method with stress point integration for simulation of incompressible fluid-nonlinear elastic structure interaction

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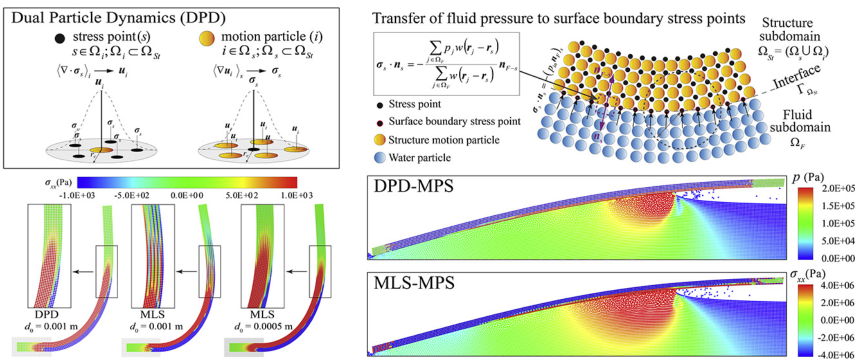
GRAPHICAL ABSTRACT



HIGHLIGHTS

- Stress point integration is utilized in particle-based modeling of FSI.
- Nonlinear structure models with nodal and stress point integrations are compared.
- The structure models are coupled with enhanced MPS-based fluid model.
- By setting stress points on the boundaries, a new version of coupling is achieved.
- Clear improvements are obtained in suppressing zero energy modes in FSI modeling.

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ABSTRACT

A fully-Lagrangian particle-based computational method is developed for simulation of incompressible Fluid, non-linear Structure Interaction (FSI) with incorporation of stress point integration (Randles and Libersky, 2005) to resolve instabilities related to zero-energy modes. Structural dynamics is founded on discretization of the divergence of stress according to Moving Least Squares (MLS) method. The stress point integration is incorporated in calculation of structural dynamics, resulting in a Dual Particle Dynamics (DPD) structure model (Randles and Libersky, 2005). A structure model based on nodal integration is also considered for comparison and simply referred to as MLS. The DPD and

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Dual Particle Dynamics
Moving Least Squares
Moving Particle Semi-Implicit

MLS structure models are coupled with an enhanced projection-based Moving Particle Semi-implicit (MPS) method as the fluid model, resulting in DPD–MPS and MLS–MPS FSI solvers, respectively. The enhanced performance of DPD with respect to MLS is first shown through a set of tests for structure model. Then the superior performance of DPD–MPS FSI solver with respect to MLS–MPS one is demonstrated through a set of FSI benchmark tests. The present study also presents a new algorithm for fluid–structure coupling via components of stress tensors in surface boundary stress points.

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1. Introduction

Complex dynamics of highly interactive systems related to violent fluid flows and structures (e.g. hydrodynamic slamming on marine vessels, tsunami/storm surge impact on onshore structures, sloshing in liquid containers, etc.) have been considered as substantial challenges in various fields of industry, highlighting the need for a precise and comprehensive modeling of these important Fluid–Structure Interaction (FSI) problems. With respect to the intrinsic difficulties usually encountered in simulation of FSI problems (i.e. existence of violent free-surface flows, large/abrupt hydrodynamic loads and consequently large structural deformations), Lagrangian mesh-free methods or so-called particle methods are appropriate candidates for computational modeling of challenging FSI problems (Gotoh and Khayyer, 2016; Shadloo et al., 2016).

Particle methods, e.g. Smoothed Particle Hydrodynamics, SPH (Liu and Liu, 2003; Violeau, 2012) or Moving Particle Semi-implicit, MPS (Koshizuka, 2011; Gotoh et al., 2013; Gotoh and Okayasu, 2017) have been coupled with various computational methods for FSI simulations. Examples include coupled MPS–superposition method (Sun et al., 2016b), coupled Discrete Element Method–SPH (Wu et al., 2016), coupled SPH Shell-Boundary Element Method (Zhang et al., 2013), and coupled Finite Element Method (FEM)–SPH (Fourey et al., 2010; Yang et al., 2012; Caleyron et al., 2013; Li et al., 2014, 2015; Siemann and Langrand, 2017; Fourey et al., 2017).

On the other hand, several studies have targeted FSI simulation in the framework of integrated fully-Lagrangian mesh-free methods. Implementation of integrated fully-Lagrangian solvers can potentially lead to an accurate and consistent imposition of fluid–structure interface boundary conditions (e.g. Antoci et al., 2007; Rafiee and Thiagarajan, 2009; Oger et al., 2010; Eghtesad et al., 2012; Hwang et al., 2014, 2015, 2016). Despite taking advantage of potentially robust Lagrangian formulation, particle methods have been prone to specific deficiencies including linear inconsistency, tensile instability and rank deficiency (zero-energy modes). In the process of advancement of FSI solvers, in line with other branches of particle-based computational mechanics, researchers have put efforts toward improvement of prevalent instabilities associated with FSI particle-based modeling.

In order to satisfy the consistency in reproduction of linear pressure/stress fields, corrective matrices (Randles and Libersky, 1996; Krongauz and Belytschko, 1998; Bonet and Kulasegaram, 2002; Bonet et al., 2004; Khayyer and Gotoh, 2011) have been employed in gradient and divergence models of SPH/MPS FSI solvers. Fourey et al. (2010) employed the coupled FEM–SPH for simulation of violent FSI problems. In the SPH-based fluid model, they applied normalized matrix for calculation of gradient of pressure. Hwang et al. (2014) developed enhanced fully-Lagrangian computational method based on projection-based MPS method. In calculation of pressure gradient, they used the Gradient Correction (GC) scheme by Khayyer and Gotoh (2011).

Tensile instability (Swegle et al., 1995) results from application of an Eulerian kernel (expressed in terms of current configuration) with a Lagrangian description of motion (Rabczuk et al., 2004). Application of a Lagrangian kernel (Belytschko et al., 2000; Belytschko and Xiao, 2000) expressed in terms of material coordinate (or reference configuration) resolves the tensile instability problem. Bonet and Kulasegaram (2001) discussed tensile instability in non-linear continuum mechanics and showed that this instability can be eliminated by using a total Lagrangian formulation where all derivatives of the kernel functions are computed at fixed reference configurations. Oger et al. (2010) simulated several test cases associated with hydroelastic slamming and showed that using a Lagrangian kernel, the structure model is protected against tensile instability. Through using a Lagrangian kernel in the structure model of an enhanced MPS-based FSI solver, Hwang et al. (2014, 2015, 2016) guaranteed the structural response against tensile instability. As highlighted by Vidal et al. (2007), utilization of a total Lagrangian framework does not eliminate the spurious oscillations associated with zero-energy modes (or so-called rank deficiency), since the origin of this instability is not related the state of the stress.

The present study focuses on instabilities related to rank deficiency or zero-energy modes in particle-based FSI modeling. To the best knowledge of authors, this class of instability has not been targeted in previous studies of fully-Lagrangian particle-based FSI solvers corresponding to beam and plate elements. Rank deficiency is mainly rooted in implementation of nodal integration, i.e. when field variables and their derivatives are estimated at the same computational set of nodes/particles (Vignjevic et al., 2000). This instability appears in terms of spurious singular modes in the reproduced responses regardless of the state of the stress (Xiao and Belytschko, 2005).

Various methods have been implemented so far for suppressing the spurious zero-energy modes in continuum mechanics simulations. In this regard, Chen et al. (2007) proposed a conforming nodal integration with a stabilization scheme for spurious non-zero energy modes, to achieve coercivity in the limit of discretization. Chen et al. (2013) derived the condition for arbitrary high order Galerkin exactness based on variational consistency. Hillman et al. (2014) carried out a comparative

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