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A Three-Field Smoothed Formulation for Prediction of Large-Displacement Fluid-Structure Interaction via the Explicit Relaxed Interface Coupling (ERIC) Scheme

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Abstract. A three-field smoothed formulation is proposed in this paper for the resolution of fluid-structure interaction (FSI) from the arbitrary Lagrangian–Eulerian perspective. The idea behind the proposed approach lies in different smoothing concepts. Both fluid and solid stress tensors are smoothly treated by the cell-based smoothed finite element method (CS-FEM) using four-node quadrilateral elements. In particular, the smoothed characteristic-based split technique is developed for the incompressible flows whereas the geometrically nonlinear solid is settled through CS-FEM as usual. The deformable mesh, often represented by a pseudo-structural system, is further tuned with the aid of a hybrid smoothing algorithm. The Explicit Relaxed Interface Coupling (ERIC) scheme is presented to interpret the nonlinear FSI effect, where all interacting fields are explicitly coupled in alliance with interface relaxation method for numerical stability. The promising ERIC solver is in detail validated against the previously published data for a large-displacement FSI benchmark. The good agreement is revealed in computed results and well-known flow-induced phenomena are accurately captured.

AMS subject classifications: 35Q30, 65M22, 65M60, 74F10, 76M10

Key words: Fluid-structure interaction, vortex-induced vibration, ALE, explicit coupling, smoothed finite element method.

1 Introduction

Many realistic flow problems require reliable fluid-structure interaction (FSI) solvers, such as vortex-induced vibrations (VIV) of marine risers subjected to ocean currents and high-rise buildings under the wind action. Once the natural frequency approaches to the

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vortex-shedding frequency and the structural damping is small enough, violently self-excited vibrations of an engineering structure will be triggered under FSI. In this case the safety of the structure may not be guaranteed. With the aid of FSI simulators, people can accurately predict the flow-structure interplay, then uncover the relevant formation mechanism, and finally work out the countermeasures to suppress the adverse responses.

The coupled FSI system can be viewed as a three-field nonlinear formulation, namely computational fluid dynamics, computational structural dynamics and computational mesh dynamics [1, 2]. Partitioned solution strategies under the arbitrary Lagrangian–Eulerian (ALE) description are generally favored for the numerical solution of such a three-field system. Therefore, different disciplines are strategically solved in a sequential manner so that existing codes are adopted with minimal modifications. Partitioned approaches are typically classified into explicit coupling algorithm [3] and implicit coupling algorithm [4–6]. From the computational viewpoint, the former is very efficient while the latter exactly satisfies the interfacial equilibrium. Explicit coupling method is highly suitable for use in aeroelasticity, especially at large mass ratio or low Reynolds number [7]. However, if the structure is quite flexible or undergoes finite deformation, explicit coupling method may suffer from severe instability due to added-mass effect [8,9]. As a consequence, special measures to ensure numerical stability are recommended for explicit coupling techniques since a good balance between accuracy and efficiency is strongly desired for practical purpose.

Gradient smoothing is a helpful technique to stabilize nodal integration in Galerkin meshless methods [10, 11]. In examining meshless and finite element methods, Liu and his colleagues found it a valuable alliance of these two methods. Their finding leads to the smoothed finite element method (SFEM) that resolves various mechanics problems by incorporation of gradient smoothing operation into the traditional FEM [12]. The essential idea behind SFEM consists in modification of the compatible strain field (from the viewpoint of solid mechanics), whereby a Galerkin model may deliver some superior properties. This technique is saliently featured by its "softened" stiffness matrix which yields more accurate solution to discrete partial differential equations than the standard FEM at the expense of easy implementation and low computational cost. For the moment, the method has been made accessible to the FSI realm where the solid component is handled by the so-called cell-based smoothed finite element method (CS-FEM). For instance, the immersed SFEM is developed to analyze FSI problems [13–16]. Specifically, SFEM in association with explicit time integration is utilized for largely deformable nonlinear solids while the characteristic-based split (CBS) scheme [17, 18] is utilized for the incompressible viscous fluid. Wang *et al.* [19] integrated the strong-form gradient smoothing method in fluid mechanics with SFEM in solid mechanics via the explicit coupling scheme. Recently, the author has applied CS-FEM to account for the finite deformation triggered by fluidic excitation under the ALE description [6, 20–22]. In spite of the accomplishments, these scenarios seem an instinctive prolongation of SFEM's early success, rather than a settlement customized for the Navier–Stokes (NS) equations that is crucial to FSI.

It is well known that the flow velocity and pressure variables tightly twine around