A Fully Stabilized Combined Field Formulation for Coupled Fluid-Structure Interactions

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We present a fully coupled three dimensional formulation based on arbitrary Lagrangian-Eulerian (ALE) approach with exact interface tracking for nonlinear fluid-structure interactions. This formulation is second order accurate in time and stable for very low mass ratios of $O(10^{-3})$. The proposed formulation is an extension of the combined field with explicit interface (CFEI) presented in [1, 2] for two-dimensional framework. The CFEI is a monolithic nonlinear coupled fluid-structure formulation with explicit/implicit time integration. In the CFEI formulation the fluid-structure interface is explicitly determined at the start of each time step. This enables decoupling of ALE mesh from the remaining variables (structural velocity, fluid velocity and pressure) and consequently requires an explicit treatment of convective velocity. Hence, the CFEI formulation needs to solve the system of linear equations only once per time step. Additionally, the combined field formulation [2] absorbs the traction and velocity continuity equations into its weak form resulting in lesser number of linear equations per time step.

The CFEI formulation in [1] is based on mixed-finite element approach to satisfy the so-called Babuska-Brezzi (LBB) or inf-sup condition. This approach can exhibit oscillatory solution for convective dominant problems. In order to overcome this, the proposed three dimensional formulation uses Galerkin/Least Squares (GLS) stabilized finite element method. Since the convective velocity is determined explicitly, the proposed solver does not require nonlinear Newtons iteration.

To demonstrate the numerical stability and accuracy of the proposed formulation, we perform a series of direct numerical simulations on the cylinder-elastic bar problem and the obtained numerical solutions are compared with the benchmark data available in literature. The temporal accuracy of the formulation is verified by numerical experiments on an elastic semi- circular cylinder problem. Finally, we illustrate the full three-dimensional nonlinear flapping dynamics of a thin flexible foil in a uniform axial flow for low mass ratios of $O(10^{-3})$ and Reynolds number 1000. Through a series of systematic direct numerical simulations we demonstrate the effect of flapping amplitudes on the three dimensionality of the wake structures. Finally, we compare the three dimensional flapping dynamics with its two dimensional counter-part [3].

Keywords: Fluid-structure interactions, Galerkin/Least Squares, combined field, flapping dynamics, three dimensional simulations.

References

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