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Deformable bodies in a 3-dimensional viscous flow: Vorticity-stream vector formulation

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Abstract-

When simulating three-dimensional flows interacting with deformable and elastic obstacles, current methods often encounter complexities in the governing equations and challenges in numerical implementation. In this work, we introduce a novel numerical formulation for simulating incompressible viscous flows at low Reynolds numbers in the presence of deformable interfaces. Our method employs a vorticity-stream vector formulation that significantly simplifies the fluid solver, transforming it into a set of coupled Poisson problems. The body–fluid interface is modeled using a phase field, allowing for the incorporation of various free-energy models to account for membrane bending and surface tension. In contrast to existing three-dimensional approaches, such as lattice Boltzmann methods or boundary-integral techniques, our formulation is lightweight and grounded in classical fluid mechanics principles, making it implementable with standard finite-difference techniques. We demonstrate the capabilities of our method by simulating the evolution of a single vesicle or droplet in Newtonian Poiseuille and Couette flows under different free-energy models, successfully recovering canonical axisymmetric shapes and stress profiles. Although this work primarily focuses on single-body dynamics in Newtonian suspending fluids, the framework can be extended to include body forces, inertial effects, and viscoelastic media.

Index Terms- Microfluídica (Microfluidics); Dinámica de Fluidos Computacional (CFD); Flujo viscoso (Viscous flow); Biomecánica celular (Cell biomechanics): Bajo número de Reynolds (Low Reynolds number); Vorticidad (Vorticity); Campo de fase (Phase-field)

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