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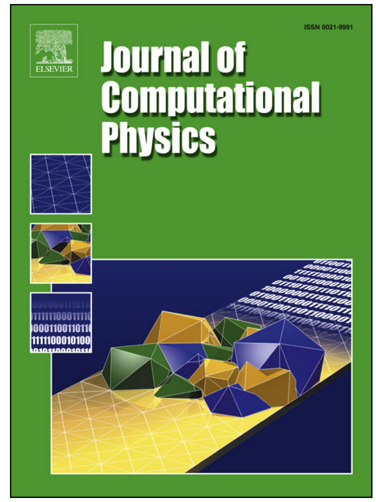

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A strongly-coupled immersed-boundary formulation for thin elastic structures

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Abstract

We present a strongly-coupled immersed-boundary method for flow-structure interaction problems involving thin deforming bodies. The method is stable for arbitrary choices of solid-to-fluid mass ratios and for large body motions. As with many strongly-coupled immersed-boundary methods, our method requires the solution of a nonlinear algebraic system at each time step. The system is solved through iteration, where the iterates are obtained by linearizing the system and performing a block-LU factorization. This restricts all iterations to small-dimensional subsystems that scale with the number of discretization points on the immersed surface, rather than on the entire flow domain. Moreover, the iteration procedure we propose does not involve heuristic regularization parameters, and has converged in a small number of iterations for all problems we have considered. We derive our method for general deforming surfaces, and verify the method with two-dimensional test problems of geometrically nonlinear flags undergoing large amplitude flapping behavior.

Keywords: flow structure interaction, projection method, strong coupling, immersed-boundary

1. Introduction

The immersed-boundary (IB) method treats the fluid and immersed body with separate grids, which obviates the need for computationally expensive tasks like re-meshing. For this reason, IB methods are often used in flow-structure interaction (FSI) problems with bodies undergoing large deformations and rotations. Yet, efficiently handling the interface constraint, which nonlinearly couples the fluid and structure, remains a challenge. We restrict our attention here to strongly-coupled IB methods, which strictly enforce the constraint. Weakly coupled IB methods do not impose the constraint, and are unstable for small solid-to-fluid mass ratios and large body motions [1–3].

Due to the nonlinear nature of the constraint, most strongly-coupled methods must solve a large nonlinear system of equations at each time step. The block Gauss-Seidel procedure is one approach to solving this nonlinear system. It is attractive for its ease of implementation, but requires relaxation to converge for a wide range of mass ratios. Employing relaxation requires a heuristically chosen parameter, and can involve dozens of iterations to converge for small mass ratios [4], though Wang and Eldredge [5] improved this convergence behavior using information about the system's added mass. Alternatively, the nonlinear system can be solved with a Newton-Raphson method. This removes the need of free parameters, and typically requires a small number of iterations irrespective of the mass ratio. However, this approach often involves computing several matrix-vector products per time step, each involving large Jacobian matrices [6–8].

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