Numerical Simulation of Fluid-Structure Interaction in Soft Cylindrical Actuators

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Abstract

This study presents a computational analysis of fluid-structure interactions involving a soft membrane in an 2D axisymmetric settings, using the continuous forcing Immersed Boundary Method (IBM). The flexible membrane undergoes significant deformations and is modeled using both linear and nonlinear constitutive relationships. The governing equations for the homogeneous isotropic axisymmetric membrane are derived using the variational asymptotic method, as prior implemented by Steigmann (1) and Ali et al. (2).
The fluid is treated as a Newtonian fluid under laminar flow conditions, governed by the 2D axisymmetric Navier-Stokes equations. The incompressible Navier-Stokes equations are solved numerically using Chorin's Projection method. The IBM employs continuous forcing to handle the interaction between the fluid and the membrane, enabling the structural geometry to remain independent of the fluid's Cartesian grid. Two-way coupling is achieved between the Eulerian grid and the Lagrangian nodes through a smoothing function. The membrane exerts forces on the fluid, while the fluid's velocity is interpolated onto the membrane nodes at the interface. Various smoothing functions (3, 4) can be used depending on the application.

The stability of the IBM algorithm is significantly influenced by factors such as geometry, discretization, material properties, flow conditions, and smoothing kernel parameters. A Python-based solver has been developed to simulate several cases like transverse fluid impact on the membrane, deformation of a perturbed membrane in a static fluid and axisymmetric actuator (where the fluid flows inside a cylindrical tube). The resulting solutions effectively capture velocity profiles, pressure distributions, and boundary layer dynamics at the interface. The framework can be used to simulate various biomechanics and soft robotics simulations.

References

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