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An immersed-boundary method for flow–structure interaction in biological systems with application to phonation

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Abstract

A new numerical approach for modeling a class of flow–structure interaction problems typically encountered in biological systems is presented. In this approach, a previously developed, sharp-interface, immersed-boundary method for incompressible flows is used to model the fluid flow and a new, sharp-interface Cartesian grid, immersed-boundary method is devised to solve the equations of linear viscoelasticity that governs the solid. The two solvers are coupled to model flow–structure interaction. This coupled solver has the advantage of simple grid generation and efficient computation on simple, single-block structured grids. The accuracy of the solid-mechanics solver is examined by applying it to a canonical problem. The solution methodology is then applied to the problem of laryngeal aerodynamics and vocal fold vibration during human phonation. This includes a three-dimensional eigen analysis for a multi-layered vocal fold prototype as well as two-dimensional, flow-induced vocal fold vibration in a modeled larynx. Several salient features of the aerodynamics as well as vocal fold dynamics are presented.

Keywords: Immersed-boundary method; Elasticity; Flow–structure interaction; Bio-flow mechanics; Phonation; Laryngeal flow; Flow-induced vibration

1. Introduction

Flow–structure interaction (FSI) is a common phenomenon in biological systems. Typical examples related to biomedical engineering include the cardiovascular system (heart valves and arteries), and the larynx. The ability to computationally model the flow–structure interaction in these systems could help us understand

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the underlying biophysics, investigate pathologies, and potentially advance medical treatments. Structural flexibility and flow–induced deformation is also ubiquitous in nature. For instance, flow–structure interaction is a key feature in biological locomotion including fish/mammalian swimming [1] and insect/bird flight, and the ability to model this interaction is important in learning the underlying physics of these modes of locomotion.

One of the main challenges in developing such biophysical models is handling of the complex and moving anatomical geometries. The finite-element method (FEM) is the traditional way of dealing with complicated computational domains (e.g. [2,3]). However, grid generation and solution of the associated algebraic equations can be quite expensive. Furthermore, biological configurations present a singularly difficult proposition for such methods given the highly complex geometries, motions, deformation and material properties that are usually encountered in these configurations.

In recent years, the immersed-boundary (IB) method has gained popularity in computational fluid dynamics (CFD) for handling complex and/or moving boundaries. In the IB method, a structured, usually Cartesian, grid which does not conform to the flow boundary is used for discretizing the governing equations [4]. Recent review on the IB method and its variants can be found in Mittal and Iaccarino [5]. Compared to the boundary-conforming structured and unstructured methods, the IB method has the advantages of simple grid generation [4] and ease of incorporating multigrid [6] and domain-decomposition based parallel algorithms [7].

The Cartesian grid based IB method has also been applied in the computation of solid-mechanics. For example, Sethian and Wiegmann [8] used a type of IB method to solve linear elastostatics on arbitrary two-dimensional domains and the solution was used in an optimization procedure to iteratively improve structural design. In their approach, a level-set method was used to represent the boundaries of the solid body, and an immersed-boundary method based on Li and LeVeque [9] and Li [10] was used to prescribe the discontinuities in the governing equations across the solid/void boundary. This approach allowed them to change the geometry and topology of the structure during the optimization process without modifying the underlying grid.

Udaykumar and coworkers [11,12] used an Eulerian method to simulate high-speed multi-material impact. Their method was based on a fixed Cartesian grid and a sharp-interface IB method was used to deal with large deformations of the material–material and material–void interfaces. The approach was particularly attractive in that the issues associated with severe mesh distortion and entangling, which would be faced by conventional body-conformal methods, can be circumvented.

In this paper, we present a Cartesian grid based approach for modeling a class of FSI problems typically encountered in biological applications. More specifically, we employ the previous sharp-interface IB method [13,7,14] to solve the Navier–Stokes equations that govern the flow, and devise a new IB formulation that allows us to compute the linear elastodynamics of complex three-dimensional (3D) structures. FSI is accomplished by operating the two solvers in a coupled manner. Compared to the IB methods described in [8,11,12], our method can be used for simulating dynamics of linearly elastic or viscoelastic solids as well as flow-induced deformation of such solids. The FSI solver is also designed to solve two- as well as three-dimensional problems and is therefore very well suited for high-fidelity modeling of biological configurations.

Although the IB method we present here for the 3D linear viscoelasticity is inspired from the approach developed in the context of the fluid dynamics by Mittal and coworkers [13,7,14] and therefore bears some similarity to that approach, the implementation is significantly different, especially with regard to the treatment of the traction boundary condition which is a unique feature of solid dynamics. This issue is discussed in detail in Section 2. It should also be noted that this method is different from the IB method described in Li and coworkers [9,10] and Sethian and Wiegmann [8]. In their methods, the solution experiences discontinuities across the singular interface immersed in the domain, and the finite-difference formulas involving the nodes across the interface were corrected by using Taylor's series around the interface and taking into consideration of the discontinuities. In contrast, our method is based on a ghost-cell methodology where the ghost-node value is a smooth extrapolation from the solution on the physical side of the boundary. There is no discontinuity involved at the boundary in our method. Furthermore, those methods require derivation of the correction term in the finite-difference formulas near the boundary, which in our view is inconvenient if applied to the 3D elasticity. In comparison, the finite-difference equations in our method are standard formulations and are thus much simpler.