Preface

Special Issue on Fluid Motion Driven by Immersed Structures

There has been tremendous progress in the development and application of advanced computational techniques for simulating the motion of an incompressible fluid driven by flexible immersed structures, in large part owing to the multitude of applications in physiology and biology. Active biological tissue is typically constructed of fibers that are surrounded by fluid; the fibers not only hold the tissue together but also transmit forces that ultimately result in fluid motion. In other cases, the fluid may flow through flexible conduits such as blood vessels or airways that both react to and affect the fluid dynamics. Additional examples arise in the context of external fluid flows in biological and engineering applications, such as dynamics of insect wings, flagellated or ciliated organisms, suspensions of blood cells and other synthetic particles, parachute dynamics, and so on.

Given the interest in the modeling and methodology related to fluid-structure interactions problems, a workshop was organized on Fluid Motion Driven by Immersed Structures, which convened August 9–13 2010 at the Fields Institute in Toronto, Canada. The workshop brought together mathematicians, computational scientists, biologists and engineers having an interest in solving fluid-structure interaction problems, with the ultimate aim being to initiate new research collaborations that improve on existing techniques and generate ideas for new approaches. This volume contains invited and refereed papers submitted by workshop speakers that were accepted after peer review.

The first paper in this volume is a review by Hou, Wang, and Layton on numerical methods for fluid-structure interactions. Many different approaches have been proposed and applied to these problems; this volume and the Fields workshop cover only a small fraction of them. One of the most ubiquitous methods for simulating fluid-structure interactions, in which the structure is subject to large deformations, is the immersed boundary method. The method was originally developed by Charles Peskin in 1971 to simulate the flow of blood in the heart, and in the ensuing decades has undergone numerous modifications and enhancements by Peskin, McQueen and collaborators. The immersed boundary method has been applied to a host of biological and engineering problems involving the interaction of a fluid with deformable, elastic structures.

In the words of Peskin, "the immersed boundary method is both a mathematical formulation and a numerical scheme." The method is based on the idea that a complex, immersed, elastic boundary is represented in a moving (Lagrangian) frame, the fluid variables in a fixed (Cartesian) frame, and the interaction between the two is governed by

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smoothed Dirac delta functions. The force generated by the immersed boundary, which appears simply as a forcing term in the incompressible Navier-Stokes equations, depends on the configuration of the material but can otherwise be very general. The primary advantage of this approach is its simplicity: complex structures reduce to isolated points at which forces are exerted on the fluid, and the fluid flow is simulated on a regular grid. The technique is therefore modular in the sense that force calculations are entirely separate from the fluid flow computations—this allows the same fluid solver to be used in different applications, the only change being in the type of boundary forces being generated. A further advantage is that new and improved fluid solvers can replace outdated ones without requiring any changes to the critical force calculations.

Much attention was given to the immersed boundary method at the workshop, which featured a keynote lecture by Lisa Fauci (Tulane University) on recent insights into swimming and pumping using an immersed boundary framework. Other presentations focused on recent advances in various versions of the immersed boundary method. This volume contains papers that focus on improvements or new formulations of the immersed boundary method, e.g., the paper by Guy and Philip, which describes a multigrid and implicit formulation of the immersed boundary method; the paper by Griffith on volume conservation; and the papers by Griffith and Lim and by Li and Song that both describe adaptive versions of the method. Other papers describe applications of the immersed boundary method: to viscoelastic Stokes flow (Strychalski and Guy), to foam simulation (Kim et al.), and to flow through an elastic tube (Lee et al.).

Despite the clear advantages of the immersed boundary approach, the original algorithm does suffer from a few well-known shortcomings: accuracy is limited to first order on the immersed boundary owing to the delta function approximation; errors in volume conservation are significant; numerical stiffness can be severe, particularly for explicit time discretization of forcing terms. These drawbacks are particularly important in applications in three dimensions, where high grid resolution, efficiency and robustness become essential. A number of related algorithms have been developed that specifically combat the problems of accuracy and volume conservation. To date one of the most successful immersed boundary-related algorithm is the immersed interface method, developed by Zhilin Li (North Carolina State University) and co-workers. The immersed interface method increases the accuracy of the computed solution to second order by explicitly incorporating into the finite difference scheme the known jumps in the solution and its derivatives rather than using smoothed delta functions. Standard finite difference methods are used away from the interface or boundaries; the finite difference schemes are modified locally near or on the interfaces or boundaries according to the interface relations so that high-order accuracy can be obtained in the entire solution. Li gave a keynote lecture describing the augmented immersed interface method and its application to free boundary and moving interface problems. This volume includes a paper by Li and Song, which presents an adaptive mesh refinement strategy for the immersed interface method, and a paper by Xu, on an iterative two-fluid pressure solver based on the immersed interface method.

The remainder of the workshop presentations discussed contact line problem, multiphase flow, and a number of applications of the immersed boundary and related methods to jellyfish, bleb formation, biofilm, etc. Keynote speaker John Lowengrub (University of California at Irvine) presented his work on computing the dynamics of multicomponent vesicles in the viscous fluid. Keynote speaker John Dolbow (Duke University) presented a survey on the recent advances in embedded finite element methods. Then, fittingly on the last day of the workshop, Sheldon Wang (Midwestern State University) gave a keynote lecture on current challenges of immersed methods. The final three papers in this volume contain approaches, other than immersed boundary or immersed interface methods, for solving fluid-structure interaction problems: Ii et al. developed a full Eulerian fluid-membrane coupling method; He and Huang present a constrained level set method for simulating the formation of liquid bridges; and the work by Hou et al. contains a numerical method for solving elasticity equations.

The organizers thank the Fields Institute for its support, without which the workshop would not have become such a resounding success. The program was distinguished by its mix of speakers from departments of mathematics, engineering and other application areas. Because fluid-structure interaction problems are so interdisciplinary in nature, interdisciplinary collaborations are necessary for the field to flourish. And it is indeed the hope of the organizers that this workshop and this special volume will spark new ideas and new collaborations that in turn lead to growth in this exciting field of research.

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