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Book Review

Computational Fluid Dynamics with Moving Boundaries

W. Shyy, H. S. Udaykumar, M. M. Rao, and R. W. Smith, Taylor & Francis, Bristol, PA, 1996, 285 pp., $89.95

Several of the many modern numerical methods currently used in the representation of discontinuities (boundaries, fronts, and interfaces) moving within a fluid are detailed and contrasted in this book. One is based on a moving (Lagrangian) grid, whereas another is based on a fixed (Eulerian) grid, providing ideal material for a pedagogical discussion of algorithmic issues such as range of applicability and topological generality. The authors state that their intent is to illustrate the applicability of their methods "for the numerical solution of moving boundary problems within the framework of the finite volume approach." Attention is focused on two specific methods as applied to selected interfacial flows; hence the book cannot by itself serve as a self-contained and general reference on computational fluid dynamics for moving boundaries. This book is timely and important, however, because it addresses numerical methods for two applications (materials processing and fluid-flexible structure interaction) for which comprehensive and realistic simulations have only recently been considered possible.

The material in this book is well written and presented in a clear and organized fashion. Each of the seven chapters begins with an introduction stating its objectives and relation to previous chapters, and each concludes with a summary of the material covered. There are no example problems or exercises, but each chapter is sprinkled with numerous figures depicting schematics and simulation results that reinforce the ideas put forth in the text. Relevant published work is cited liberally throughout (there are over 350 references). A brief description of each chapter follows.

Chapter 1 presents a brief introduction to the book, wherein the authors provide a chapter-by-chapter overview and cite many interesting physical processes involving interfaces that both move under the influence of the flowfield and in turn affect the behavior of the flow. Here the authors exhibit their knowledge of this wide and growing field, especially pertaining to those techniques pioneered and used by others. Although some parts of this survey are sprinkled with opinion (which is refreshing!), it provides an extremely useful service to anyone curious about the host of numerical methods that have been tried and are available for the problems of interest to this book.

Chapter 2 begins with an excellent summary of most of the seminal works on incompressible Navier–Stokes solution methods developed over the past three decades. The model system, written in body-fitted coordinates, consists of the two-dimensional Navier–Stokes equations (with arbitrary source terms and a Boussinesq approximation) and an enthalpy equation (with diffusion and source terms). There follows a short section on the authors' Navier–Stokes solution method, which is a staggered-mesh SIMPLE algorithm modified for a body-fitted mesh that can move arbitrarily. Brief explanations of key issues such as consistent velocity interpolation and mesh movement (with a Jacobian evolution equation) are particularly useful. Simulation results for rotated channel flow and uniform flow on a moving grid nicely amplify the authors' points. Missing are discussions of monotone-preserving upwind schemes (central differences are used instead) and comments on the strengths and weaknesses of their SIMPLE algorithm relative to other popular schemes. The chapter concludes with an intriguing section on the float zone technique, which is a candidate method for growing single crystals. Discussions of meniscus shape estimation, energy transport (conduction/convection) scaling, and surface tension effects enumerate the complex physical processes present in a float zone. The float zone simulations that follow assume that the interface is static; hence the mesh remains fixed. This float zone section nicely illustrates the ability of a body-fitted coordinate method to simulate complex physical processes driven by interfacial physics (in this case interfacial surface tension and heat flux). The results presented indicate the importance of Marangoni convection effects.

In Chapter 3 the applicability of the body-fitted coordinate solution method detailed in Chapter 2 is extended by modeling a system characterized by a moving interface, which in this case is a flexible membrane wing. The mesh must now move because one of its grid lines remains attached to the moving membrane wing. Here the interest is in the interaction of laminar, incompressible Navier–Stokes flow with a (massless) membrane, e.g., a sail, having tension that in general depends on both prestress and strain. The membrane motion is governed by a Young–Laplace relation wherein the pressure jump across the membrane (given by Navier–Stokes solutions) is given by the product of the local membrane curvature and tension. The difficult numerical issue is the efficient coupling of the membrane relation with the Navier–Stokes solution. The authors invoke a successive-substitution iteration scheme in which the membrane relation and Navier–Stokes equations are solved alternately, using the latest solutions available, which requires thousands of iterations to reach steady state. Comments regarding this scheme, i.e., whether it might be improved, would have been useful. Nevertheless, the flexible membrane wing results in this chapter are quite impressive, as they provide evidence for the usefulness of full Navier–Stokes simulations as opposed to potential flow approximations.

Chapter 4 focuses on the application of the aforementioned moving-grid method to modeling pure material solidification. Here a portion of the grid, e.g., a logical line of constant i or j, remains on a moving solid/liquid interface, with the remainder of the grid conforming accordingly. After a brief historical perspective, various physical mechanisms influencing the shape and morphological stability of the solid/liquid interface in pure metal solidification are discussed. Solutions to a Neumann solidification problem (one-dimensional conduction/solidification) are then obtained with the authors' moving-grid boundary-fitted methodology. Comparisons are made with analytical solutions, and errors induced by neglecting terms involving grid movement in the boundary-fitted evolution equations are analyzed. The chapter concludes with numerical solutions for an example in which solid/liquid interfacial curvature and surface tension must be taken into account.

In many practical situations involving solidification, it is not necessary to simulate the problem with an algorithm that explicitly tracks the solid/liquid interface. Chapter 5 discusses the application of space-averaged methods in modeling solidification problems. These methods are computationally less complicated because solid/liquid interfaces are captured rather than tracked. The chapter begins with an interesting discussion of scales involved in solidification systems. The governing energy conservation equation for space-averaged methods is then presented in both a temperature-based and an enthalpy-based formulation. Performance of the numerical method put forth by the authors (other methods are available in the literature) for solving these formulations is assessed with a one-dimensional pure material phase change problem. Next, governing equations with convection are presented. Finally, simulation results for a few practical problems involving isothermal phase change are presented.

In Chapter 6 the authors' ELAFINT (Eulerian–Lagrangian Algorithm for Interface Tracking) algorithm is detailed and its capabilities demonstrated with computational examples of thermal diffusion-controlled solid/liquid phase change of pure materials. The conceptual basis for the ELAFINT algorithm, namely the use of massless "marker particles" to delineate interfaces on a fixed, logically connected, orthogonal mesh, is not new, having originated over three decades ago. This approach is attractive because of its ability to model interfaces having arbitrarily complex topology. This type of interface tracking scheme, which falls within the general class of front tracking methods, has been pursued and refined in two and three dimensions by other researchers in addition to the authors, e.g., J. Glimm and G. Tryggvason for compressible and incompressible flow applications, respectively. Although the basic approach is not new or unique, the detailed discussion of the assumptions, implementation (data structures and logic), and discretization of the ELAFINT algorithm is refreshing and long overdue for a front tracking method. Many researchers are hesitant to implement and use front tracking methods because of the perceived algorithm complexity of such methods. This chapter goes a long way toward refuting the notion that front tracking methods are too complicated and lack robustness (even in two dimensions) for reliable use in modeling real applications. A few questions arise in reading this chapter, however, such as whether this algorithm can be easily extended to three dimensions, how this algorithm compares to other front tracking methods, whether the logically connected, orthogonal mesh assumptions can be relaxed, and whether the mass conservation properties and convergence behavior are sufficient.

Chapter 7 concludes the book with a brief assessment of the authors' fixed-grid ELAFINT algorithm, which is performed by comparing its solution quality to the authors' moving-grid curvilinear coordinate-based algorithm. Three two-dimensional problems are chosen for the comparison: driven-cavity flow in a box having a cosine-shaped bottom, natural convection flow in the same box, and a gallium melting front propagation problem. The two flow problems possess internal rigid boundaries (the cosine-shaped box bottom), and the gallium problem possesses a propagating interface (the gallium melting front); hence they are problems representative of many moving-boundary flows found in nature and industry, with one exception: the boundaries in these problems lack topological complexity. Not surprisingly, then, the ELAFINT and curvilinear-based coordinate methods exhibit solutions that are essentially indiscernible. Since fixed-grid algorithm development and use is typically motivated by the need to model topologically complex boundaries, problems possessing boundaries with more challenging geometries might have been more appropriate. Complex boundary problems are more likely to delineate the conditions for which a fixed-grid technique might lose accuracy or fail. This chapter is nevertheless useful, as it dares to broach a subject (controlled side-by-side algorithm comparisons) that remains woefully lacking in the literature.

This book is recommended as a supplementary reference for students, teachers, and researchers interested in modern numerical methods for incompressible flows possessing moving boundaries. It will be particularly useful for those interested in modeling the boundaries with a (particle-based) fixed-grid method or a (curvilinear coordinate-based) moving-grid method. Because of its focus on a few (out of many possible) methods as applied to specific flow examples found in materials processing and fluid-flexible structure interaction, this book is not a comprehensive and independent reference on this broad subject. It will not readily serve as an independent text in a graduate-level course because example problems are missing and algorithm detail, e.g., templates, is sparse in places. If you are in need of a modern reference on selected numerical methods for flows possessing moving boundaries, this book should be in your library. It will undoubtedly stimulate further progress in this exciting area.

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