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Computational Fluid-Structure Interaction

Methods and Applications

Yuri Bazilevs, Kenji Takizawa and Tayfun E. Tezduyar

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COMPUTATIONAL FLUID–STRUCTURE INTERACTION

METHODS AND APPLICATIONS

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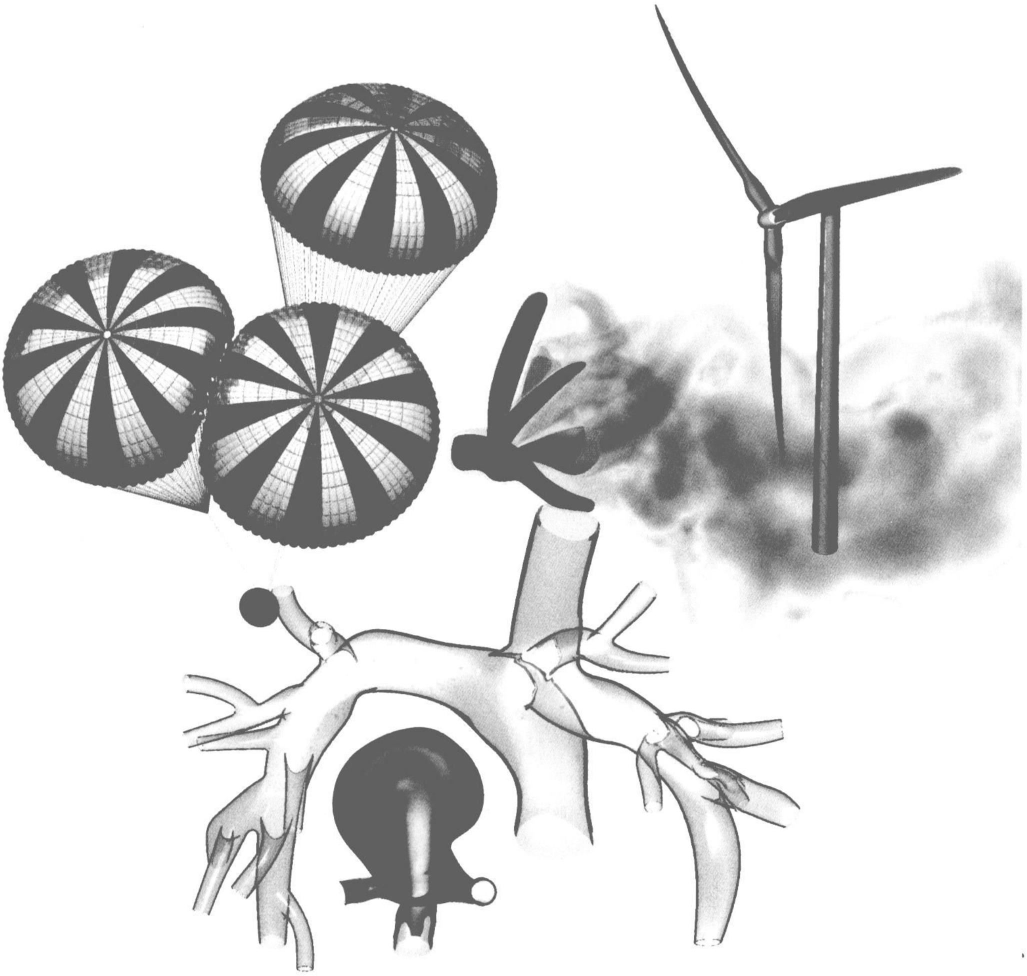

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Series Preface

The series on *Computational Mechanics* is a conveniently identifiable set of books covering interrelated subjects that have been receiving much attention in recent years and need to have a place in senior undergraduate and graduate school curricula, and in engineering practice. The subjects will cover applications and methods categories. They will range from biomechanics to fluid–structure interactions to multiscale mechanics and from computational geometry to meshfree techniques to parallel and iterative computing methods. Application areas will be across the board in a wide range of industries, including civil, mechanical, aerospace, automotive, environmental and biomedical engineering. Practicing engineers, researchers and software developers at universities, industry and government laboratories, and graduate students will find this book series to be an indispensible source for new engineering approaches, interdisciplinary research, and a comprehensive learning experience in computational mechanics.

Computational Fluid–Structure Interaction has seen rapid developments over the past decade. The present book, written by a team of prominent researchers, gives a comprehensive treatment of modern developments in the field and fills a gap in the literature. Starting from basic concepts in computational fluid and structural mechanics, it explains the computational methods used in the analysis of fluid–structure interaction problems in a clear and accessible manner. The book stands out in that not only standard finite element methods are used for the spatial discretization, but that space–time and isogeometric finite element methods are also covered, thus emphasizing the state-of-the-art character of the book. The later chapters provide a plethora of examples and applications – ranging from cardiovascular problems, the aerodynamics of flapping wings, wind turbine blades to the simulation of parachutes – all taken from the vast research experience of the authors in the field.

Preface

Significance of FSI

Fluid–structure interaction (FSI) is a class of problems with mutual dependence between the fluid and structural mechanics parts. The flow behavior depends on the shape of the structure and its motion, and the motion and deformation of the structure depend on the fluid mechanics forces acting on the structure. We see FSI almost everywhere in engineering, sciences, and medicine, and also in our daily lives. The FSI effects become more significant and noticeable when the dependence between the influence and response becomes stronger. The fluttering of aircraft wings, flapping of an airport windsock, deflection of wind-turbine blades, falling of a leaf, inflation of automobile airbags, dynamics of spacecraft parachutes, rocking motion of ships, pumping of blood by the ventricles of the human heart, accompanied by the opening and closing of the heart valves, and blood flow and arterial dynamics in cerebral aneurysms, are all FSI examples. In engineering applications, FSI plays an important role and influences the decisions that go into the design of systems of contemporary interest. Therefore, truly predictive FSI methods, which help address these problems of interest, are in high demand in industry, research laboratories, medical fields, space exploration, and many other contexts.

Role of Computational FSI

The inherently nonlinear and time-dependent nature of FSI makes it very difficult to use analytical methods in this class of problems. Only a handful of cases have been studied analytically, where simplifying assumptions have been invoked to arrive at closed-form solutions of the underlying partial differential equations. While we see some use of analytical methods in solution of fluid-only or structure-only problems, there are very few such developments in solution of FSI problems. In contrast, there have been significant advances in computational FSI research, especially in recent decades, in both core FSI methods forming a general framework and special FSI methods targeting specific classes of problems (see, for example, Tezduyar, 1992; Tezduyar *et al.*, 1992a,c; Morand and Ohayon, 1995; Tezduyar, 2003a; Michler *et al.*, 2003, 2004; van Brummelen and de Borst, 2005; Lohner *et al.*, 2006; Dettmer and Peric, 2006; Tezduyar *et al.*, 2006a; Tezduyar and Sathe, 2007; Bazilevs *et al.*, 2007a, 2008; Dettmer and Peric, 2008; Idelsohn *et al.*, 2008a,b; Cottrell *et al.*, 2009; Takizawa and Tezduyar, 2011, 2012a; Takizawa *et al.*, 2012a; Takizawa and Tezduyar, 2012b; Bazilevs *et al.*, 2012b). Computational methods, which are robust, efficient, and capable of accurately modeling in 3D FSI with geometrically complex configurations at full spatial scales, have been the focal point of these advances.

Computational FSI Challenges

The challenges involved in computational FSI can be categorized into three areas: *problem formulation*, *numerical discretization*, and *fluid–structure coupling*. These challenges are summarized here.

The problem formulation takes place at the continuous level, before the discretization. However, one must keep in mind that the modeling choices made at the continuous level have implications for the numerical discretizations that are most suitable for the case at hand. In a typical single-field mechanics problem, such as a fluid-only or structure-only problem, one begins with a set of governing differential equations in the problem domain and a set of boundary conditions on the domain boundary. The domain may or may not be in motion. The situation is more complicated in an FSI problem. The sets of differential equations and boundary conditions associated with the fluid and structure domains must be satisfied simultaneously. The domains do not overlap, and the two systems are coupled at the fluid–structure interface, which requires a set of physically meaningful interface conditions. These coupling conditions are the compatibility of the kinematics and tractions at the fluid–structure interface. The structure domain is in motion and, in most cases, its motion follows the material particles, or points, which constitute the structure. This is known as the *Lagrangian description* of the structural motion. As the structure moves through space, the shape of the fluid subdomain changes to conform to the motion of the structure. The motion of the fluid mechanics domain needs to be accounted for in the differential equations and boundary conditions. There are two major classes of methods for this, which are known in the discrete setting as the *nonmoving-grid* and *moving-grid* approaches. Furthermore, the motion of the fluid domain is not known a priori. It is a function of the unknown structural displacement. This makes FSI a three-field problem, where the third unknown is the motion of the fluid domain.

All the issues related to the numerical discretization of a single-field problem, such as the accuracy, stability, robustness, speed of execution, and the ability to handle complex geometries, are likewise present in an FSI problem. The additional challenges in FSI come from the discretization at the fluid–structure interface. The most flexible option is, of course, to have separate fluid and structure discretizations for the individual subproblems, which results in nonmatching meshes at the interface. In this case, one needs to ensure that, despite the nonmatching interface meshes, the fluid and structure have the correct coupling of the kinematics and tractions. A simpler option is to have matching discretizations at the fluid–structure interface. In this case, the satisfaction of the FSI coupling conditions is much less challenging. However, this choice leads to a lack of flexibility in the discretization choices and mesh refinement levels for the fluid and structure subproblems. That flexibility becomes increasingly important as the complexity of the fluid–structure interface geometry increases. On the other hand, there are situations where having matching discretizations at the interface is the most effective approach. Another computational challenge in some FSI applications is the need to accommodate very large structural motions. In this case, one needs a robust mesh moving technique and the option to periodically regenerate the fluid mechanics mesh (i.e., remesh) to preserve the mesh quality and consequently the accuracy of the FSI computations. The remeshing procedure requires the interpolation of the solution from the old mesh to the new one. Remeshing and data interpolation are also necessary for fluid-only computations over domains with known motion. The difference between that and FSI is that the remeshing can be precomputed in such fluid-only simulations, while in the case of FSI the fluid mechanics mesh quality depends on the unknown structural displacements, and the decision to remesh is made "on the fly."

There are two major classes of FSI coupling techniques: loosely-coupled and strongly-coupled, which are also referred to as staggered and monolithic, respectively. Monolithic coupling often refers to strong coupling with matching interface discretizations. In loosely-coupled approaches, the equations of fluid mechanics, structural mechanics, and mesh moving are solved sequentially. For a given time step, a typical loosely-coupled algorithm involves the solution of the fluid mechanics equations with the velocity boundary conditions coming from the extrapolated structure displacement rate at the interface, followed by the solution of the structural mechanics equations with the updated fluid mechanics interface traction, and followed by the solution of the mesh moving equations with the updated structural displacement at the interface. This enables the use of existing fluid and structure solvers, a significant motivation for adopting this approach. In addition, for several problems the staggered approach works well and is very efficient. However, convergence difficulties are encountered sometimes, most-commonly when the structure is light and the fluid is heavy, and when an incompressible fluid is fully enclosed by the structure. In strongly-coupled approaches, the equations of fluid, structure, and mesh moving are solved simultaneously, in a fully-coupled fashion. The main advantage is that strongly-coupled solvers are more robust. Many of the problems encountered with the staggered approaches are avoided. However, strongly-coupled approaches necessitate writing a fully-integrated FSI solver, virtually precluding the use of existing fluid and structure solvers. There are three categories of coupling techniques in strongly-coupled FSI methods: block-iterative, quasi-direct, and direct coupling. The methods are ranked according to the level of coupling between the blocks of the left-hand-side matrix. In all three cases, iterations are performed within a time step to simultaneously converge the solutions of all the equations involved.

Organization of the Chapters

The three categories of FSI computational challenges outlined above constitute the bulk of the book's content.

In Chapter 1, the boundary value problems associated with the fluid and structural mechanics are stated. The fluid mechanics modeling is restricted to incompressible flows. This is mainly due to the principal research interests of the authors. The presentation of the structural mechanics covers 3D solids and thin structures. The latter includes shells, membranes, and cables. The equations of fluid mechanics in a moving spatial domain are also presented, and the fundamental concepts of space–time and Arbitrary Lagrangian–Eulerian (ALE) formulations are introduced. Both the conservative and convective forms of the Navier–Stokes equations of incompressible flows, in the ALE frame, are derived, and the implications for the conservation properties of the corresponding discrete FSI formulations are discussed.

Chapter 2 is on the basics of the finite element method (FEM). The presentation is confined to nonmoving spatial domains. Examples of time-dependent advection–diffusion, linear-elasticity, and Navier–Stokes equations discretized with the FEM are presented. In this book the FEM and Isogeometric Analysis (IGA) are employed for the discretization of the fluid and structural mechanics equations. IGA is a newly developed computational method that is based on the basis function technology of Computer-Aided Design (CAD) and Computer Graphics (CG), which was developed to provide a tighter integration between engineering design and analysis. In this chapter, the basics of stabilized and multiscale methods for fluid mechanics are also introduced. These methods possess superior stability properties compared to their Galerkin counterparts, while retaining the full order of accuracy. The chapter concludes with the presentation of weakly enforced essential boundary conditions, which enhance the accuracy of the stabilized and multiscale formulations in the presence of unresolved thin boundary layers, which are seen near solid boundaries.

The basic concepts of IGA are presented in Chapter 3. The presentation is focused on IGA based on non-Uniform Rational B-Splines (NURBS). For more in-depth understanding of this new computational technology, the reader is referred to Cottrell *et al.* (2009).

Chapter 4 is focused on the FEM for fluid mechanics problems with moving boundaries and interfaces. ALE and space–time FEM are covered in detail. The fully discrete stabilized and multiscale formulations of the fluid mechanics problem are presented for both approaches. In the case of the ALE approach, the FEM semi-discretization is followed by a presentation of the generalized-α time integration algorithm. In the case of space–time FEM, because both space and time behavior is approximated with finite element functions, the method leads to a fully discrete system of nonlinear equations at every time step. The standard mesh update strategy, which is based on the equations of linear elastostatics driven by the time-dependent displacement of the fluid mechanics domain boundary, is discussed at the end of the chapter.

In Chapter 5, the FSI problem is formulated at the continuous level and in the weak form. It is shown that the weak form, with the appropriate kinematic constraints on the trial and test function sets, gives the FSI formulation with the correct coupling conditions at the fluid–structure interface. The semi-discrete ALE FSI formulation, with the assumption of matching fluid–structure discretizations at the interface, is presented. The generalized-α method and the corresponding predictor–multicorrector algorithm are extended to the FSI problem. The linearization of the discrete FSI equation system is also discussed in the context of the ALE formulation. The space–time FSI formulation is presented next. The requirement of the matching interface discretizations is removed and several treatment options for nonmatching interface discretizations are discussed. Advanced mesh moving and remeshing techniques are outlined at the end of the chapter.

Chapter 6 presents the advanced FSI and space–time techniques the authors introduced, which include FSI coupling techniques, matrix-free computation techniques, segregated linear equation solvers, and preconditioning strategies. The chapter includes methods introduced for using temporal NURBS basis functions, in the context of the space–time formulation, in representation of the motion and deformation of the moving surfaces and volume meshes, and in remeshing. The chapter concludes with an FSI contact algorithm.

Chapter 7 presents a selection of representative FSI computations, which are used to explain some of the computational challenges faced in real-world applications. The test cases presented, and the computational methods used to solve them, address the challenges of FSI in fully-enclosed domains, as well as in the presence of structures that undergo large deformations and topological changes at the fluid–structure interface. Computational aerodynamics of flapping-wings with video-captured wing motion and deformation patterns of an actual locust is also presented. This illustrates the challenges of moving-domain fluid mechanics simulations in the presence of multiple surfaces undergoing large relative motions.

Chapters 8–10 present the applications of the FSI methods developed by the authors and their research groups to cardiovascular biomechanics, parachutes, and wind-turbine rotors. In all cases, the modeling and simulations are performed in 3D and at full spatial and temporal scales involved in these physical systems. In all three classes of FSI problems, the *core FSI technologies* are those presented in the earlier chapters. However, successful FSI computations require also the development of special FSI techniques targeting these specific classes of problems. The special techniques for each of the three classes of FSI problems are presented together with the computational results.

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