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EDITORIAL

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The analytical approach, which lies at the basis of the exact and natural sciences, rests on the notion that complex systems can be reduced to simple components. This divide-and-conquer approach has shaped contemporary science and technology, and has formed the foundation for virtually all scientific breakthroughs in the 19th and 20th century. It is also the origin of the separation of mechanics into fluid and solid mechanics, so much so that these branches of mechanics are commonly considered as distinct scientific disciplines. Notably, the disconnection between fluid and solid mechanics is evidenced by the tremendous advancements in computational methods and commercial simulation codes for fluid- and solid-mechanical systems separately, as compared to the relative underdevelopment of commercial codes for fluid-structure-interaction analyses.

With the advancement of analysis capabilities for fluid- and structure-mechanics systems separately, emerged the realization that many problems in science and engineering cannot be appropriately categorized as either a fluid or structure problem, but are fundamentally determined by the interaction of a fluid and a solid. Examples are flutter and buffet instabilities in aerospace and civil engineering, the functioning of heart valves in biomechanics, sloshing and vibrations in flexible fluid containers and fluid conduits, deployment of inflatable structures such as airbeams and airbags, and deformation of soft substrates due to capillary forces, for example, in microfluidic applications and biomechanics. The development of computational methods for fluid-structure-interaction problems commenced in the early 1980s and many important foundations were laid in the 1990s. Despite the significant progress that has been made since then in computational models and methods for Fluid-Structure Interaction (FSI), many open challenges still remain, and computational FSI continues to be an active area of investigation and development.

This special issue presents an overview of *vanguard developments in computational methods for fluid-structure interaction*. The 12 manuscripts in this special issue cover a variety of contemporary topics in computational FSI.

The development of efficient and robust partitioned solution methods continues to be an important branch of research in computational FSI. Such partitioned solution methods allow to retain the modularity of the fluid and structure subsystems, thus enabling the reuse of the complete gamut of advanced commercial and open-source simulation software for fluid-dynamics and solid-dynamics problems separately. In this special issue, Cao et al. present a spatially-varying Robin coupling condition to mitigate the added-mass effect of incompressible flows in FSI in partitioned solution procedures.[1] In a similar vein, Dettmer et al. present a new combined two-field relaxation strategy to enhance the stability of the standard Dirichlet–Neumann FSI coupling strategy in the presence of strong added-mass effects.[2] The work by Rüth et al. is concerned with the development of quasi-Newton waveform relaxation techniques to enable efficient and robust partitioned iterative solution strategies supporting multi-rate approximations (or *subcycling*), and the implementation of this multi-rate coupling strategy in the open-source coupling software preCICE.[3]

Another important contemporary development in computational fluid-structure interaction, pertains to FSI in conjunction with auxiliary physical subsystems. A main class of problems of this type, are fluid-structure-contact-interaction (FSCI) problems, that is, problems in which the structure subsystem exhibits (self-)contact. A fundamental challenge in FSCI problems, is that the fluid domain generally exhibits a topological change at contact. In this special issue, Hiromi-Spühler and Hoffman present a unified continuum model for fluid-structure interaction with full-friction contact with application to aortic valves.[4] As opposed to the moving-mesh approach considered by Hiromi-Spühler and Hoffman, the manuscript by Ager et al. is concerned with an immersed (CutFEM) FSCI formulation, in which a continuous transition from the standard no-slip condition to frictionless contact is enabled by means of a generalized Navier boundary condition with variable slip coefficient.[5] A second important class of FSI problems with auxiliary interactions, pertains to FSI of free-boundary flows, that is, FSI problems in which the fluid subsystem itself exhibits a free surface or an interface between distinct fluid components. As capillary effects on the fluid meniscus generally play a crucial role in the behavior of these problems, this class of problems is commonly referred to as *elasto-capillarity* or, in the case that the fluid subsystem is comprised of two distinct species separated by an interface, as *binary-fluid–structure interaction* (BFSI). An essential complication in elasto-capillary FSI pertains to the modeling of the contact line, that is, the triple point corresponding to the intersection of the fluid meniscus with the fluid-structure interface. Ohayon et al. present a new formulation for modeling the effects of sloshing of an acoustic fluid with a free-boundary with capillary effects in an elastic container.[6] The manuscript by van Brummelen et al. presents an adaptive simulation framework for elasto-capillary FSI in which the fluid–fluid meniscus is modeled as a diffuse interface via the Navier–Stokes–Cahn–Hilliard equations, which intrinsically accounts for the motion of the contact line.[7]

Immersed and embedded boundary methods are taking an increasingly important position in computational FSI, by virtue of their geometric flexibility. In addition to the manuscript by Ager et al. this special issue features three manuscripts on this subject. A fundamental difficulty in immersed-FSI methods concerns the fact that the topology and geometry of the intersection of the fluid-structure interface with the background mesh evolve in an essentially arbitrary manner during the FSI dynamics, compromising stability and accuracy of the FSI formulation. Ho and Farhat present an embedded boundary method in which the fluid equations and, correspondingly, system outputs depend smoothly on the position of the interface, that is, discrete events associated with changes in the topology of the mesh-interface intersection are eliminated.[8] Fernández and Gerosa introduce a stable coupling scheme for immersed FSI, based on a projective semi-implicit splitting paradigm in combination with a Nitsche-type formulation.[9] Huang et al. present a special immersed-FSI approach for solid subsystems of co-dimension two, such as cables, booms and risers.[10]

The tremendous recent progress in computational FSI has also enabled the use of FSI simulations in multi-disciplinary control, design, optimization and inversion problems. Such control and optimization problems pose severe conditions on the stability and consistency of the FSI formulation, as well as on the efficiency of the computational procedure. In this special issue, Wick and Wollner present a monolithic formulation for gradient-based optimization for unsteady FSI problems, based on the adjoint-equation formalism.[11] Boncoraglio et al. consider a new model-reduction framework to enhance the efficiency of multi-parameter FSI optimization problems with linearized FSI constraints.[12]

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REFERENCES

1. Cao S, Wang G, Wang KG. A spatially varying Robin interface condition for fluid-structure coupled simulations. *Int J Numer Methods Eng*. 2021;122(19):5176-5203. https://doi.org/10.1002/nme.6386
2. Dettmer WG, Lovrić A, Kadapa C, Perić D. New iterative and staggered solution schemes for incompressible fluid-structure interaction based on Dirichlet-Neumann coupling. *Int J Numer Methods Eng*. 2021;122(19):5204-5235. https://doi.org/10.1002/nme.6494
3. Rüth B, Uekermann B, Mehl M, Birken P, Monge A, Bungartz HJ. Quasi-Newton waveform iteration for partitioned surface-coupled multiphysics applications. *Int J Numer Methods Eng*. 2021;122(19):5236-5257. https://doi.org/10.1002/nme.6443
4. Hiromi Spühler J, Hoffman J. An interface-tracking unified continuum model for fluid-structure interaction with topology change and full-friction contact with application to aortic valves. *Int J Numer Methods Eng*. 2021;122(19):5258-5278. https://doi.org/10.1002/nme.6384
5. Ager C, Seitz A, Wall WA. A consistent and versatile computational approach for general fluid-structure-contact interaction problems. *Int J Numer Methods Eng*. 2021;122(19):5279-5312. https://doi.org/10.1002/nme.6556
6. Ohayon R, Soize C, Akkaoui Q, Capiez-Lernout E. Novel formulation for the effects of sloshing with capillarity on elastic structures in linear dynamics. *Int J Numer Methods Eng*. 2021;122(19):5313-5330. https://doi.org/10.1002/nme.6290
7. van Brummelen E, Demont T, van Zwieten G. An adaptive isogeometric analysis approach to elasto-capillary fluid-solid interaction. *Int J Numer Meth Eng*. 2021;122(19):5331-5352. https://doi.org/10.1002/nme.6388
8. Ho J, Farhat C. Discrete embedded boundary method with smooth dependence on the evolution of a fluid-structure interface. *Int J Numer Methods Eng*. 2021;122(19):5353-5383. https://doi.org/10.1002/nme.6455
9. Fernández MA, Gerosa FM. An unfitted mesh semi-implicit coupling scheme for fluid-structure interaction with immersed solids. *Int J Numer Methods Eng*. 2021;122(19):5384-5408. https://doi.org/10.1002/nme.6449

10. Huang DZ, Avery P, Farhat C. An embedded boundary approach for resolving the contribution of cable subsystems to fully coupled fluid-structure interaction. *Int J Numer Methods Eng*. 2021;122(19):5409-5429. https://doi.org/10.1002/nme.6322
11. Wick T, Wollner W. Optimization with nonstationary, nonlinear monolithic fluid-structure interaction. *Int J Numer Methods Eng*. 2021;122(19):5430-5449. https://doi.org/10.1002/nme.6372
12. Boncoraglio G, Farhat C, Bou-Mosleh C. Model reduction framework with a new take on active subspaces for optimization problems with linearized fluid-structure interaction constraints. *Int J Numer Methods Eng*. 2021;122(19):5450-5481. https://doi.org/10.1002/nme.6376