Fluid-Structure Interaction of Incompressible Flows and Thin-Walled Structures*

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Summary. A numerical approach to simulate the coupled problem of slender structures and incompressible Newtonian flows is described. The formulation is based on a partitioned scheme where finite elements are employed on the single fields. The structural field is discretized in space by finite elements based on a seven-parameter shell formulation capable of dealing with the complex dynamics of very slender structures. An efficient solver for the structural system of equations exploiting an algebraic multigrid approach has been developed. A stabilized fluid element following an ALE formulation of the incompressible Navier-Stokes equations is used to model the flow on a time dependent domain. The geometric conservation law is built into the formulation to obtain a stable scheme which is second order accurate in time. The accuracy and reliability of the approach with respect to critical parameters such as very small time steps, distorted meshes or steep gradients in particular within the flow field has been analyzed. The approach is able to also deal with free fluid surfaces.

The inherent instability of weakly coupled approaches is analyzed which reveals the devastating influence of the so-called ‘artificial added mass’ effect. The convergence of the strongly coupled approach depends on an appropriately chosen relaxation parameter. Ways to automatically adjust the proper amount of relaxation are given. Special emphasis is also put on the efficient implementation particularly of the fluid problem. Vectorization is employed to significantly speed up the time spent for calculating element matrices on vector machines.

Keywords: Fluid-structure interaction, finite elements, stabilization methods, geometric conservation law, vectorization

* Research Project B4 “Fluid-Structure Interaction of Shells”
1 Introduction

The project is concerned with the modeling and discretization of interaction phenomena of incompressible flows and thin structures. It aims at a broad spectrum of applications from engineering problems such as liquid filled containers exposed to earthquake acceleration to biomedical questions like physiological blood flow. Within previous periods of the project the general methodology and a computational environment to treat coupled multi field problems had been developed. With regard to fluid-structure interaction partitioned strategies for surface coupled problems have been addressed. A three field fluid-structure interaction solver has been developed which can be decomposed into a computational fluid dynamics (CFD) module, a nonlinear structural mechanics part (CSD) and a mesh dynamics solver (CMD). The CFD approach to model incompressible viscous flows is based on a stabilized finite element method formulated in an Arbitrary Lagrangian-Eulerian (ALE) approach which accounts for the time dependent fluid domain. The geometrically nonlinear structural dynamics is based on a three-dimensional shell formulation, mixed hybrid finite elements and direct time integration with controllable numerical damping. Quasi-elastic pseudo-structural approaches are used to model the mesh motion.

At the beginning of the final period of the project further improvements had been developed among which there are two- and three-level approaches to solve the Navier-Stokes equations and free surface formulations which had been implemented for two-dimensional fluid and fluid-structural problems. Further robust, strongly coupled partitioned solution approaches basing on an iterative Dirichlet-Neumann substructuring approach equipped with relaxation methods which accelerate or even enable convergence had been developed. Additional effort had been put into the development of iterative and parallel solution approaches for thin shells.

2 Governing Equations and Basic Assumptions

The simulation of a wide variety of complex fluid-structure interaction problems requires generally applicable models of the different physical fields along with stable, efficient and accurate discretization and solution approaches.

![Sketch of general fluid-structure interaction problem](image-url)