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A monolithic fluid-structure interaction formulation for solid and liquid membranes including free-surface contact

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Abstract

A unified fluid-structure interaction (FSI) formulation is presented for solid, liquid and mixed membranes. Nonlinear finite elements (FE) and the generalized-α scheme are used for the spatial and temporal discretization. The membrane discretization is based on curvilinear surface elements that can describe large deformations and rotations, and also provide a straightforward description for contact. The fluid is described by the incompressible Navier-Stokes equations, and its discretization is based on stabilized Petrov-Galerkin FE. The coupling between fluid and structure uses a conforming sharp interface discretization, and the resulting non-linear FE equations are solved monolithically within the Newton-Raphson scheme. An arbitrary Lagrangian-Eulerian formulation is used for the fluid in order to account for the mesh motion around the structure. The formulation is very general and admits diverse applications that include contact at free surfaces. This is demonstrated by two analytical and three numerical examples exhibiting strong coupling between fluid and structure. The examples include balloon inflation, droplet rolling and flapping flags. They span a Reynolds-number range from 0.001 to 2000. One of the examples considers the extension to rotation-free shells using isogeometric FE.

Keywords: arbitrary Lagrangian-Eulerian formulation, contact mechanics, incompressible Navier-Stokes equations, isogeometric finite elements, nonlinear membranes, surface tension

1 Introduction

Fluid-structure interaction (FSI) problems are challenging problems due to various reasons. They combine the computational challenges of (generally non-linear) fluid and structural mechanics, and they introduce new challenges, both physical and numerical, due to the coupling. If the structure is highly flexible, such as a thin membrane, large deformations can be expected. Those, in turn, have a large influence on the fluid flow. A comprehensive overview of FSI and its challenges is given by the monographs of Ohayon (2004), Bazilevs et al. (2013) and Bazilevs and Takizawa (2016). The classical focus in FSI problems is on solid structures. However, some structures are not solids but rather fluids or fluid-like objects. Examples are liquid menisci, soap films and lipid bilayers. Lipid bilayers surround biological cells. They are characterized by both solid-like (i.e. elastic bending) and fluid-like behavior (i.e. in-plane flow). Further, liquid (and solid) membranes can come into contact with surrounding objects. A classical example is a liquid droplet rolling on a substrate. The problem is characterized by fluid flow, surface tension and contact.

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