Accepted Manuscript

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PII: S0045-7825(18)30170-1
DOI: https://doi.org/10.1016/j.cma.2018.03.045
Reference: CMA 11851

To appear in: *Comput. Methods Appl. Mech. Engrg.*

Received date : 1 November 2017
Revised date : 5 March 2018
Accepted date : 31 March 2018

Please cite this article as: J. Liu, A.L. Marsden, A unified continuum and variational multiscale formulation for fluids, solids, and fluid–structure interaction, *Comput. Methods Appl. Mech. Engrg.* (2018), https://doi.org/10.1016/j.cma.2018.03.045

A unified continuum and variational multiscale formulation for fluids, solids, and fluid-structure interaction

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Abstract

We develop a unified continuum modeling framework using the Gibbs free energy as the thermodynamic potential. This framework naturally leads to a pressure primitive variable formulation for the continuum body, which is well-behaved in both compressible and incompressible regimes. Our derivation also provides a rational justification of the isochoric-volumetric additive split of free energies in nonlinear elasticity. The variational multiscale analysis is performed for the continuum model to construct a foundation for numerical discretization. We first consider the continuum body instantiated as a hyperelastic material and develop a variational multiscale formulation for the hyper-elastodynamic problem. The generalized-α method is applied for temporal discretization. A segregated algorithm for the nonlinear solver, based on the original idea introduced in [107], is carefully analyzed. Second, we apply the new formulation to construct a novel unified formulation for fluid-solid coupled problems. The variational multiscale formulation is utilized for spatial discretization in both fluid and solid subdomains. The generalized-α method is applied for the whole continuum body, and optimal high-frequency dissipation is achieved in both fluid and solid subproblems. A new predictor multi-corrector algorithm is developed based on the segregated algorithm. The efficacy of the new formulations is examined in several benchmark problems. The results indicate that the proposed modeling and numerical methodologies constitute a promising technology for biomedical and engineering applications, particularly those necessitating incompressible models.

Keywords: Nonlinear continuum mechanics, Incompressible solids, Gibbs free energy, Variational Multiscale Method, Generalized-α method, Fluid-structure interaction

1. Introduction

Continued advancement in the variational multiscale (VMS) method for computational fluid dynamics (CFD) [5, 59, 131], multiscale boundary conditions to model the distal vasculature [126], numerical optimization methods [84, 129], novel coupling procedures for fluid-structure integration (FSI) [7, 30, 92], and new solver technologies [90, 91] have led to increasingly sophisticated simulation technologies of three-dimensional patient-specific cardiovascular problems [83, 85, 117]. These simulation methods have been applied to investigate a wide range of cardiovascular problems with increasing clinical utility, such as coronary artery disease [100], aneurysms [72], and congenital heart disease [130]. These advances have also led to new open problems and a call for new computational technologies in biomedical modeling [118]. In particular, there is a pressing need to accurately predict transmural stresses for nonlinear, anisotropic, nearly incompressible, viscoelastic materials in the setting of FSI. This technology will benefit the investigation of long-term vascular growth and remodeling driven by mechanical forces and mechanobiological response. This work represents our first step towards developing a robust, stable, accurate, and efficient finite element technology to address the aforementioned need. We focus on (1) constructing a unified modeling framework

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