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A unifying model for fluid flow and elastic solid deformation: A novel approach for fluid–structure interaction

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ABSTRACT

Fluid–structure coupling is addressed through a unified equation for compressible Newtonian fluid flow and elastic solid deformation. This is done by introducing thermodynamics within Cauchy's equation through the isothermal compressibility coefficient that is experimentally measurable for both fluids and solids. The vectorial resolution of the governing equation, where every component of velocity vectors and displacement variation vectors is calculated simultaneously in the overall multi-phase system, is characteristic of a monolithic resolution involving no iterative coupling. For system equation closure, mass density and pressure are both re-actualized from velocity vector divergence, when the shear stress tensor within the solid phase is re-actualized from the displacement variation vectors. This novel approach is first validated on a two-phase system, involving a plane fluid–solid interface, through the two following test cases: (i) steady-state compression and (ii) longitudinal and transverse elastic wave propagations. Then the 3D study of compressive fluid injection towards an elastic solid is analyzed from initial time to steady-state evolution.

1. Introduction

Fluid flow and solid deformation coupling as well as wave propagation is important concerns in many applications in aeronautics (Farhat et al., 2006; Cavagna et al., 2007) and biomedicine (Barker and Cai, 2010; Quaini et al., 2012). This multiphysics problem involving fluid–structure interaction (FSI) can be simulated in a partitioned or monolithic way. In partitioned approaches (Cavagna et al., 2007; Yigit et al., 2008; Degroote, et al., 2010a,b; Jaiman et al., 2011; Breuer et al., 2012), fluid and structure equations are resolved sequentially which may result in numerical instabilities due to different time integration schemes for fluid and solid solvers. For monolithic approaches (Barker and Cai, 2010; Quaini et al., 2012), the fluid–structure interaction at the interface is resolved simultaneously using iterative coupling schemes leading to numerical stability but involving time-consuming calculation. The Arbitrary Lagrangian Eulerian (ALE) (Huerta and Liu, 1988; Turek and Hron, 2006; Farhat et al., 2006; Murea, 2010; Richter and Wick, 2010; Sambasivan and UdayKumar, 2010) method is one of the monolithic methods used for viscous flow governed by Navier–Stokes equations which also have the advantage of being able to deal with strictly separated material discretization as mesh movement techniques for block-structured grids can do (Yigit et al., 2008). This is not the case for the Eulerian method based on Cartesian grid

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and non-conforming interface, which has given rise to many numerical developments either within partitioned (Jaiman et al., 2011; Banks et al., 2012) or monolithic (Kloppel et al., 2011; Robinson-Mosher et al., 2011) procedures to increase the accuracy of the coupling between the two materials at the interface. The lattice Boltzmann method (LBM) and the Immersed Boundary methods (IBM) are other classes of numerical approaches, less accurate than the ALE methods, which can nevertheless deal with fluid–structure interaction more easily in case of unsteady flows around flexible objects (Zhang and Gay, 2007; Lee and Lee, 2012) or bubble-like deformable objects moving in incompressible fluids (Zhang and Gay, 2007).

While algorithmic improvements are essential to deal with complex fluid–solid problems, developments of new physical models are of great importance as well. The main objective of this work is thus to propose a unifying model for fluid flow and elastic solid deformation. This model is an extension to elastic solid phases of a previously developed model dedicated to compressible multi-phase flows (Caltagirone et al., 2011).

2. Unified multi-phase compressible model for isothermal conditions

2.1. Lagrangian formulation of density and pressure

Let us consider a two-phase domain Ω delimited by a surface Γ (Fig. 1). The interface between the two phases is noted Σ. No mass exchange through the interface is involved, leading to a divariant two-phase system. The thermodynamic state can thus be described at any material point M and time t with two intensive variables, the absolute temperature $T(M,t)$ and the pressure $p(M,t)$. Density $\rho(M,t)$ and every thermodynamic coefficient such as the coefficient of isothermal compressibility $\chi_T(M,t)$ can thus be defined from these two variables. Moreover, modeling of elastic solid deformation implies the introduction of a mechanical variable, the residual shear stress tensor $\tau(M,t)$.

For an evolving two-phase domain in isothermal conditions, the material point density $\rho(M,t)$ and pressure $p(M,t)$ at time t can be determined from $\rho^0(M,t^0)$ and $p^0(M,t^0)$ at time t^0 (with $t=t^0+dt$) and the knowledge of their material derivative $d\rho/dt$ and dp/dt, respectively. The material derivative of density depends on velocity divergence $\nabla\cdot\mathbf{V}$ through the mass conservation equation

$$\frac{d\rho}{dt}=-\rho\,\nabla\cdot\mathbf{V}. \tag{1}$$

At constant temperature, the material derivative of pressure only depends on the velocity divergence through the relation

$$\frac{dp}{dt}=\left(\frac{\partial p}{\partial\rho}\right)_T\frac{d\rho}{dt}=-\frac{1}{\chi_T}\nabla\cdot\mathbf{V}. \tag{2}$$

The Lagrangian form of density and pressure at time t can thus be written at constant temperature as follows:

$$\begin{cases} p=p^0-\dfrac{dt}{\chi_T}\nabla\cdot\mathbf{V} \\ \rho=\rho^0\mathrm{e}^{-dt\,\nabla\cdot\mathbf{V}} \end{cases}. \tag{3}$$

where the isothermal compressibility coefficient χ_T is defined by using the intensive variable values T and p^0 at time t^0.

2.2. Lagrangian unified governing equation

The formulation of the governing equation is developed within the Lagrangian representation. For simplicity, we omit to indicate the material M-point for the variables.

For isothermal conditions, the governing equation of the mechanical problem is the conservation of momentum $\rho\mathbf{V}$ defined through Cauchy's equation

$$\rho\frac{d\mathbf{V}}{dt}=\nabla\cdot\boldsymbol{\sigma}+\rho\mathbf{g}+\mathbf{f}, \tag{4}$$

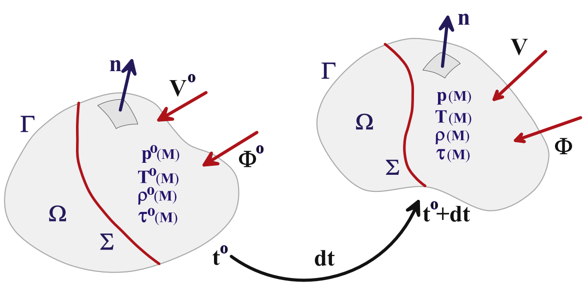

Fig. 1. Evolution of the Lagrangian variables for a material point M between time t^0 and time $t=t^0+dt$.