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Numerical modeling and investigation of viscoelastic fluid–structure interaction applying an implicit partitioned coupling algorithm

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A B S T R A C T

We investigate the interaction between a viscoelastic Oldroyd-B fluid and an elastic structure via simulations applying an implicit partitioned coupling algorithm. Simulations are done for a flow through a channel with a flexible wall and a lid-driven cavity flow with flexible bottom. In addition, we make use of a mass–spring–dashpot prototype model to study the dynamic interaction problem. Both the simulation results and the analysis of the prototype model show that there are obvious differences in the fluid–structure interaction if the fluids are viscoelastic instead of purely viscous. These differences appear in the deformation of the solid at stationary state and in the equilibrium position, amplitude, frequency as well as phase shift of the oscillation. Moreover, we investigate the influence of numerical and physical parameters on the implicit partitioned coupling algorithm for simulation of viscoelastic fluid–structure interaction problems.

1. Introduction

Fluid–structure interaction (FSI) is frequently encountered in many applications, in particular, in biomedical research. A well-known example is the blood flow in arteries or veins, where information generated by investigation of blood vessel–wall interaction is useful for medical evaluation. Another example concerns micro-organisms like bacteria, algae or sperm swimming in body fluids. Here, understanding the propulsion mechanisms opens an avenue for the control of biological systems and the design of artificial micro-machines, e.g. micro-valves, micro-pumps or micro-robots which are employed to carry out local and small-scale micro-operations. For such micro-devices FSI also plays an important role. For instance, in a valveless membrane micro-pump, the vibrating membrane drives the fluid flow, meanwhile, the fluid strongly influences the resistance to this vibration.

In the FSI problems mentioned, fluids usually have non-Newtonian fluid properties. In particular, viscoelastic behaviour often occurs, i.e. the fluids exhibit both viscous and elastic characteristics under typical flow conditions. For such viscoelastic

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fluid–structure interaction (VFSI) problems the effect of viscoelasticity may play a crucial role when it is comparable to or even dominates inertia effects. For instance, due to this fact the swimming of micro-organisms requires swimming strategies different from those in the macroscopic world.

Studying FSI problems in biomedical research via experiments is difficult and costly. Therefore, the research is increasingly aided through numerical modeling. Techniques for numerical modeling of FSI with Newtonian fluids have been developed for decades. They serve well as a guide in industrial and scientific applications. FSI with generalized Newtonian fluids, such as fluids with shear-dependent viscosity has been studied via numerical modeling for several years. Representative works are, e.g., Lukáčová-Medvid'ová and Zaušková (2008) and Lukáčová-Medvid'ová et al. (2013). The extra stress tensor $\boldsymbol{\tau}$ of generalized Newtonian fluids has the form $\boldsymbol{\tau} = 2\eta(\dot{\gamma})\mathbf{D}$, where $\mathbf{D}$ is the rate of deformation tensor and $\dot{\gamma} = \sqrt{2\mathbf{D}:\mathbf{D}}$ is the shear rate. One can model different shear dependent non-Newtonian behaviours, such as shear-thinning, shear-thickening, by using different functional forms of $\eta(\dot{\gamma})$. A commonly used model for viscosity is given by the power law $\eta(\dot{\gamma}) = K\dot{\gamma}^{n-1}$, where K is the consistency factor and n is the power law index. Viscoelastic fluids have memory, i.e. the extra stresses depend not only on the current motion of fluid but also on the history of the motion. To model these fluids, more complex time-dependent constitutive models, e.g. Oldroyd-B, FENE-P, Giesekus, etc., must be employed. So far, not much work concerns FSI with viscoelastic fluids. As far as we know, two relevant works are done by Chakraborty et al. (2010, 2012). In both papers the simulations are carried out for fluid flowing in a two-dimensional deformable channel. The stationary deformation of the solid wall for different fluid relaxation times is investigated, but no transient behaviour of the VFSI system is studied.

It is addressed by Chakraborty et al. (2010) that one of the difficulties in simulation of VFSI is the stability problem, the so-called High Weissenberg Number Problem (HWNP), in simulation of viscoelastic fluid flow. When the HWNP occurs, computation does not converge if the Weissenberg number, which describes the ratio of elastic force to viscous force, exceeds certain critical values. The HWNP is one of the factors that hinder the progress in the research of VFSI. However, in recent years, several techniques to cope with the HWNP have been developed and successfully applied for simulation of viscoelastic fluid flows at Weissenberg numbers of practical interest. The log-conformation representation (LCR) proposed by Fattal and Kupferman (2004) is one of the successful methods among the others. It is interesting to see the effect of LCR on coping with the HWNP in VFSI and to know whether we can gain deeper insight into the VFSI problem and investigate the different behaviours between VFSI and Newtonian FSI (NFSI).

For simulation of FSI problems, a partitioned coupling algorithm is attractive, because it is flexible to adapt modern techniques in the fluid and/or structural solver. Thus, such an approach simplifies the work to integrate the techniques for HWNP into the FSI simulation. In this context the influence of numerical as well as physical parameters on the coupling algorithm is an important issue, which has not been systematically investigated so far for VFSI problems. A convenient way to analyse the convergence properties of a partitioned coupling algorithm is to apply the mass–spring–dashpot model proposed by Joosten et al. (2009). It is possible to extend this model to analyse the properties of the coupling algorithm for VFSI. Also it is possible to apply the extended prototype model to study the dynamic behaviours of a VFSI system and compare it to the simulations.

Based on the above discussion there are several questions still opening within the VFSI problems: How is the transient behaviour of a VFSI system? How is the effect of approaches coping with HWNP on simulation of VFSI problems? How is the convergence property of the partitioned coupling algorithm for VFSI? What can we learn in applying the mass–spring–dashpot model to analyse the dynamic behaviour of a VFSI system and the property of the coupling algorithm for VFSI? With the present work we will contribute to answers to those questions.

The rest of the paper is organised as follows. In Section 2 we present the governing equations of an incompressible Oldroyd-B fluid flow in a moving domain and the balance of an elastic structure. The log-conformation representation for solving the constitutive equations is described there. The numerical methods used for simulation of viscoelastic fluids and the implicit partitioned coupling algorithm for VFSI is outlined in Section 3. In Section 4 we first review the mass–spring–dashpot model proposed by Joosten et al. (2009) then extent it for a VFSI system and analyse the solutions of this prototype model. In Section 5 the simulation results of test cases "two-dimensional flow through a channel with a flexible wall" and "three-dimensional lid-driven cavity flow with flexible bottom" are discussed. Finally, conclusions are given in Section 6.

2. Governing equations

The general FSI problem consists of a fluid domain Ω^f and a structural domain Ω^s. They share a common interface Γ^i. Initially the two domains occupy Ω_0^f and Ω_0^s and the interface is located at Γ_0^i at time $t=0$ (see Fig. 1(a)). Due to the interaction between fluid and structure, the position of the interface changes to $\Gamma^i(t)$ at time t. The fluid and structure domains then deform and change to $\Omega^f(t)$ and $\Omega^s(t)$, respectively (see Fig. 1(b)).

In case of an incompressible Oldroyd-B fluid interacting with an elastic solid, the velocity $\mathbf{u}$, the pressure p as well as the extra stress τ (or the conformation tensor $\mathbf{c}$ if the conformation formulation is employed) are chosen for the unknowns in the fluid phase, whereas the displacement $\mathbf{d}$ is the unknown on the structural side.

2.1. Fluid domain

The fluid domain Ω^f varies in time due to the moving interface Γ^i. A possibility to account for the moving domain is to formulate the problem in the Arbitrary-Lagrangian–Eulerian (ALE) description, cf. Hirt et al. (1974). In the ALE description,