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Fluid-Structure Interaction in Microchannel Using Lattice Boltzmann Method and Size-Dependent Beam Element

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Abstract. Fluid-structure interaction (FSI) problems in microchannels play prominent roles in many engineering applications. The present study is an effort towards the simulation of flow in microchannel considering FSI. Top boundary of the microchannel is assumed to be rigid and the bottom boundary, which is modeled as a Bernoulli-Euler beam, is simulated by size-dependent beam elements for finite element method (FEM) based on a modified couple stress theory. The lattice Boltzmann method (LBM) using D2Q13 LB model is coupled to the FEM in order to solve fluid part of FSI problem. In the present study, the governing equations are non-dimensionalized and the set of dimensionless groups is exhibited to show their effects on micro-beam displacement. The numerical results show that the displacements of the micro-beam predicted by the size-dependent beam element are smaller than those by the classical beam element.

AMS subject classifications: 74F10, 74N15, 74A60, 80M10, 76T99

Key words: Fluid-structure interaction, microchannel, lattice Boltzmann method, size-dependent beam element.

1 Introduction

Due to the recent rapid development of micro flow devices applied in micro-total-analysis-systems (m-TAS) and micro-electro-mechanical systems (MEMS), modeling and simulation methods for flows in such micro geometries have been of great interest in the society of computational physics [1]. The design of stirrers, extruders and injection systems in process engineering or articial heart valves and blood vessels in medicine require the consideration of the bidirectional interaction between fluid and structure as well.

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In general, two approaches to solve FSI problems exist: The monolithic approach [2] discretizes the two separate domains with a similar discretization scheme and solves the resulting, coupled system of equations within one solver. The compatibility conditions at the interface are treated inherently within this system of equations. By contrast, the partitioned approach [3] uses separate solvers for the fluid and the structural system. Strong coupling methods [4] as well as loose coupling methods [5] exist. In the partitioned solution, the solvers need to communicate physical properties of their mutual boundary to fulfill the interface conditions. Each domain may utilize any type of discretization considered efficient for its field.

Several numerical techniques have been also developed for FSI problems using the macroscopic continuity and momentum equations for flow field. Some of them used FEM for both fluid and structure analyses [6, 7], and some others used coupled FEM and the boundary element method [8, 9]. Most of those studies considered potential flow for FSI. Viscous flow considered in blood flow using FEM [10, 11].

In microscale applications, microstructure-dependent size effects are often observed [12]. Beam models based on classical elasticity are not capable of describing such size effects due to the lack of a material length scale parameter. This motivated the development of beam models using higher-order (non-local) continuum theories that contain additional material constants. In view of the difficulties in determining microstructure-dependent length scale parameters [13] and the approximate nature of beam theories, non-classical beam models involving only one material length scale parameter are desirable. One such model has recently been developed for the Bernoulli-Euler beam by Park and Gao [14] using a modified couple stress theory proposed by Yang et al. [15], which contains only one material length scale parameter. The modified couple stress theory was employed to develop a size-dependent beam element able to predict the size-dependency observed in microbeams by Kahrobaiyan et al. [16].

The Navier-Stokes (macroscopic momentum) equations are, no longer applicable to micro flows (levels of moderately high Knudsen number) and the flow physics in such flows is described by the Boltzmann equation (BE) of the gas kinetic theory [17]. Moreover, an advantage of the LBM compared to conventional computational fluid dynamics (CFD) solvers is the local availability of the stress tensor. For example, problems such as multiphase flows [18], turbulent flow [19], and thermal flow [20] could be handled effectively using the LBM. The first LB algorithm for an interaction problem between a fluid and rigid obstacles has been developed by Ladd [21, 22] for the simulation of particulate suspensions. An application of the LBM to FSI was the case with flow around rigid structures as appeared in articial heart-valve geometries [23]. Moreover, Coupling of LBM to FEM for FSI application was undertaken in the staggered manner for D2Q9 LB model [24]. The D2Q9 LB model can only capture the basic feature at sufficiently small Knudsen numbers. Higher-order LB method improves the accuracy in micro flows (finite Knudsen number), as had been compared with the standard LB method. Transient bidirectional FSI problem was investigated with geometrically non-linear structural deflections [25]. However, to the best knowledge of the authors, there were few efforts to