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Lattice Boltzmann Simulations of Two Linear Microswimmers Using the Immersed Boundary Method

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Abstract. The performance of a single or the collection of microswimmers strongly depends on the hydrodynamic coupling among their constituents and themselves. We present a numerical study for a single and a pair of microswimmers based on lattice Boltzmann method (LBM) simulations. Our numerical algorithm consists of two separable parts. Lagrange polynomials provide a discretization of the microswimmers and the lattice Boltzmann method captures the dynamics of the surrounding fluid. The two components couple via an immersed boundary method. We present data for a single swimmer system and our data also show the onset of collective effects and, in particular, an overall velocity increment of clusters of swimmers.

AMS subject classifications: 74F10, 76P05, 92C05, 74B05

Key words: Immersed boundary method, lattice Boltzmann method, finite element method, microswimmer, collective motion.

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1 Introduction

In his seminal work, Purcell pointed out that the properties of microscopic objects placed in fluids are significantly different from their macroscopic counterparts [1]. In particular, Purcell showed that in order to swim in the low Reynolds number regime, a micrometric

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*Corresponding author. *Email address:* `j.harting@fz-juelich.de` (J. Harting) swimmer has to move its parts in such a manner as to break the time inversion symmetry. This fact led to the well-known "scallop theorem", which states that in order to attain self-propulsion in the low Reynolds number regime, at least two degrees of freedom are needed. Since then, numerous attempts have been done to elucidate the dynamics of microswimmers by means of theoretical models [2–14], experimental setups [15–25] and numerical simulations [26–32]. In particular, in Ref. [5] Najafi and Golestanian proposed a theoretical model that precisely fulfills the requirement of Purcell. Indeed, they offered a very simple swimmer composed of three aligned solid spherical particles suspended in a viscous fluid and actuated internally by changing the distances between neighboring particles. In a Newtonian fluid (see Refs. [33,34] for a theoretical and experimental extension of the problem in the case of the underdamped regime and non-Newtonian fluids), the dynamics of such a swimmer is fully determined by the two degrees of freedom of the swimmer, namely, the two distances among subsequent beads [6]. Later, a variation of this swimmer has been proposed, where harmonic springs connect neighboring particles and external forces drive the swimmer [3, 9]. Once actuated with a proper protocol, the motion of the three beads of the swimmer results to be non-reciprocal and hence leads to a net displacement.

Recently, the focus of theoretical research has shifted towards swimming in complex environments like channels [35, 36] or near fluid interfaces [31, 37], and the question of collective swimmer dynamics has become of major interest. The present work aims at understanding the collective dynamics of several microswimmers [38,39]. For this purpose, we consider a relatively simple situation of two linear microswimmers in different configurations. Additionally, we exploit the suitability of the employed simulation method for this task. The structure of the manuscript is as follows: In Section 2, we present the theoretical model and the numerical implementation. In Section 3, we present our numerical results for a single and two microswimmers in diverse arrangements, which are then discussed in Section 4. Finally, in Section 5 we provide some concluding remarks.

2 Model

We focus on investigating the behavior of a single and a pair of bead-spring microswimmers in a resting Newtonian fluid. Each microswimmer consists of three aligned equal beads connected with springs which is a modification [9] of the model proposed by Najafi and Golestanian [5]. The distances between the beads represent the two degrees of freedom necessary to attain self-propulsion, as per the scallop theorem [1] and depicted in Fig. 1. The microswimmer particles consist of rigid spherical shells filled with a Newtonian fluid with the same viscosity and density as the external fluid. The fluid-particle interactions are incorporated into the model through the immersed boundary method (IBM) [40]. The flow field in the entire computational domain is computed using the lattice Boltzmann method (LBM).