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An ALE-Based Finite Element Model of Flagellar Motion Driven by Beating Waves: A Parametric Study

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Abstract

A computational model of flagellar motility is presented using finite element method. Two-dimensional traveling waves of finite amplitude are propagated down the flagellum and the swimmer is propelled through a viscous fluid according to the Newton's second law of motion. Incompressible Navier-Stokes equations are solved on a triangular moving mesh and arbitrary Lagrangian-Eulerian formulation is employed to accommodate the deforming boundaries. The results from the present study are validated against the data available in the literature and close agreement with previous works is found. The effects of wave parameters as well as head morphology on the swimming characteristics are studied for different swimming conditions. We have found that the swimming velocities are linear functions of finite amplitudes and that the rate of work is independent of the channel height for large amplitudes. Furthermore, we have also demonstrated that for the range of wave parameters that are often encountered in human sperm motility studies, the propulsive velocity versus the wavelength exhibits dissimilar trends for different channel heights. Various head configurations were analyzed and it is also observed that wall proximity amplifies the effects induced by different head shapes. By taking non-Newtonian fluids into account, we present new efficiency analyses through which we have found that the model microorganism swims much more efficiently in shear-thinning fluids.

keywords

microorganisms, traveling waves, finite element method, moving mesh, non-Newtonian fluids

1. Introduction

Microscale propulsion has been one of biologists' main areas of interest for many years, since motility of these small swimmers plays a profound role in biosystems. Those particular types of bacteria that exhibit motility can move in the direction of the concentration gradient of food molecules to provide nutrition or to avoid repellants. The biology of reproduction is significantly dependent upon the propulsion of spermatozoa, which have to pass through various environments in the female reproductive tract in order to meet and fertilize the ovum. Accordingly, it is of considerable importance to analyze the motion of such swimmers in detail so as to understand how different geometric, kinematic and physical parameters affect their progression velocity, power consumption, etc. and to be able to distinguish between dominant and also less influential factors. In this paper, this objective is going to be accomplished through parametric studies of the presented flagellar model for situations that were not addressed before.

Numerical simulations of flagellar and also non-flagellar motility have been proven to be powerful tools to gain better insight into the underlying physics of such motions. Also, the emergence of microrobots and synthetic swimmers which are believed to have great potential in biomedical applications, have rendered computational tools even more important by providing invaluable data for improving and optimizing their design. The Study of microswimmers hydrodynamics was first initiated