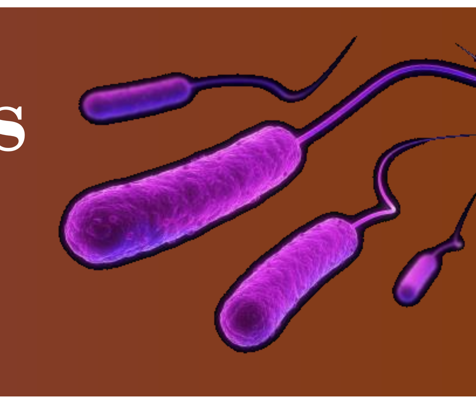

Computer Simulations of Flexibility and Inertial Effects on Self-propelled Swimming Bodies

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Abstract

In this research, a numerical simulation method is employed to simulate a flapping movement for a flexible slender swimmer in a fluid. Our objective is to study dynamic behaviors of the flapping movement. Fig. 1 shows a sketch of the simulation: the leading edge of the swimming body is swung in the vertical direction to generate a horizontal thrust force, which drives the body itself to cruise in the horizontal direction in a fluid. The simulation is based on a combination of three numerical methods: the Lattice Boltzmann Method (LBM), Lattice Spring Model (LSM), and Immersed Boundary Method (IBM). The results show that two characteristics of the swimmer, flexibility and inertia, affect the swimmer cruising direction and performance. Illustrations are given in this study to explain the underlying mechanism of these phenomena.

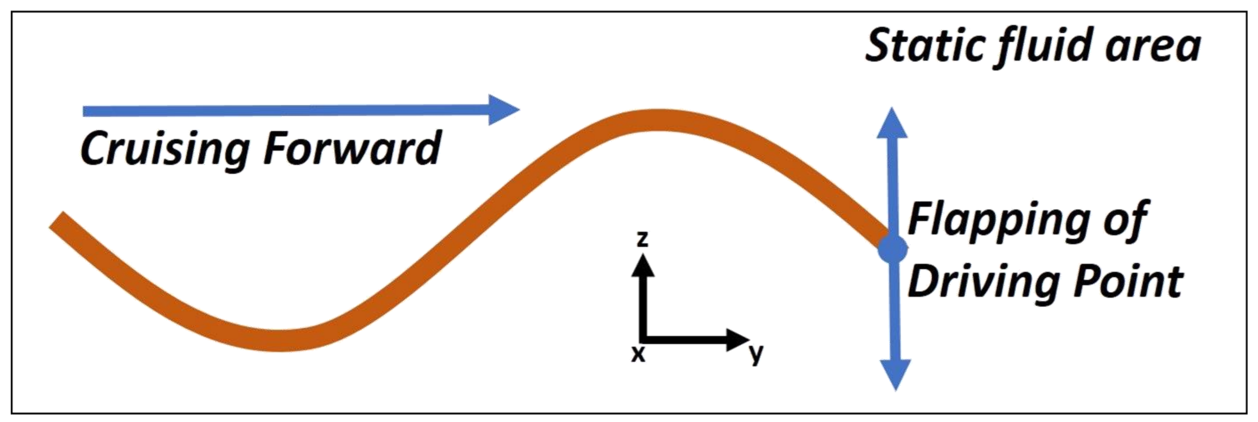

Fig. 1. A sketch of the simulation setup. The leading edge of the swimming body is swung in the vertical direction to generate a horizontal thrust force in a fluid.

Fig. 2. Flapping motion in the natural world.

Introduction

Natural frequency (f_0): the frequency at which an object tends to vibrate with in the absence of driving force when somehow disturbed.
Inertia (Π_0): The tendency of an object to resist changes. It varies with mass.

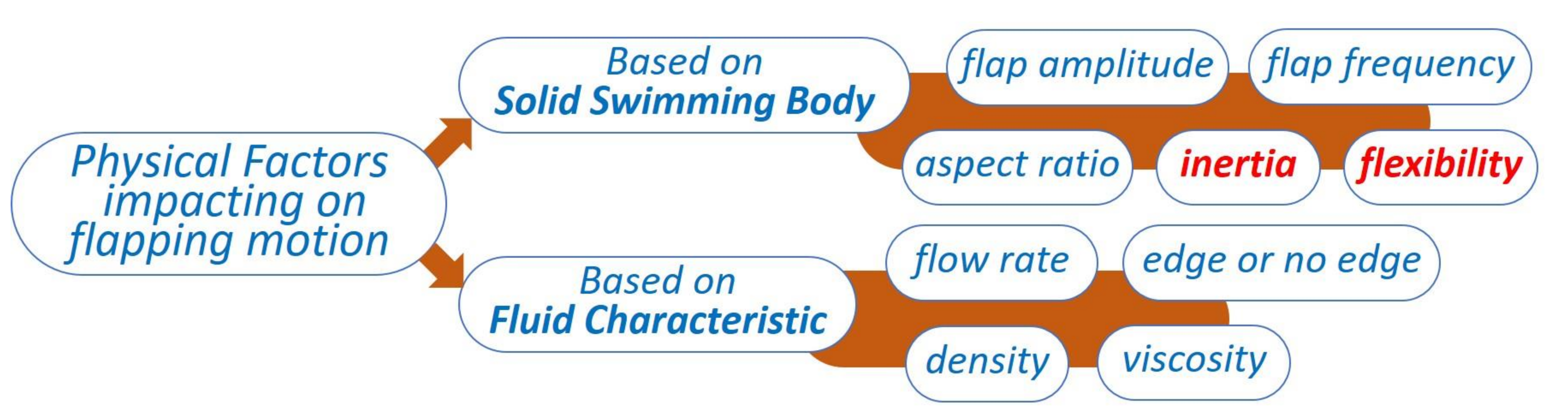

Fig. 3. Several factors may affect the flapping.

Background

A variety of creatures, such as birds, fishes, and microorganisms with filaments (see Fig. 2), employ the flapping motion to propel themselves. The mechanism of motion of the self-propelled swimmer was explored by numerous researches theoretically, experimentally, and numerically. In the field of hydrodynamics, it is widely accepted that some physical characteristics of the swimmer and fluid flow (see Fig. 3) have significant impacts on the cruising direction (forward or backward) of the swimmer. Researchers are interested in what these physical characteristics are and how they affect the direction in fluids. To understand the fundamental mechanisms of a flapping swimmer can help researchers to optimize the performance of robots in fluids, such as the Autonomous Underwater Vehicles (AUVs).

Previous studies have pointed out that two factors, flexibility and inertia of the swimmer, can manipulate the cruising direction of the swimmer [1,2,3,4]. However, their results are in two-dimension only. In this work, our simulation is running in three-dimension which makes it closer to a realistic situation.

Objectives

The purposes of this present work are
1) to simulate the flapping motion in a three-dimensional space;
2) to show the forward and backward cruising directions of a swimmer with flapping motion by varying its rigidity and inertia;
3) to explain the underlying mechanisms of these phenomena.

Methodology

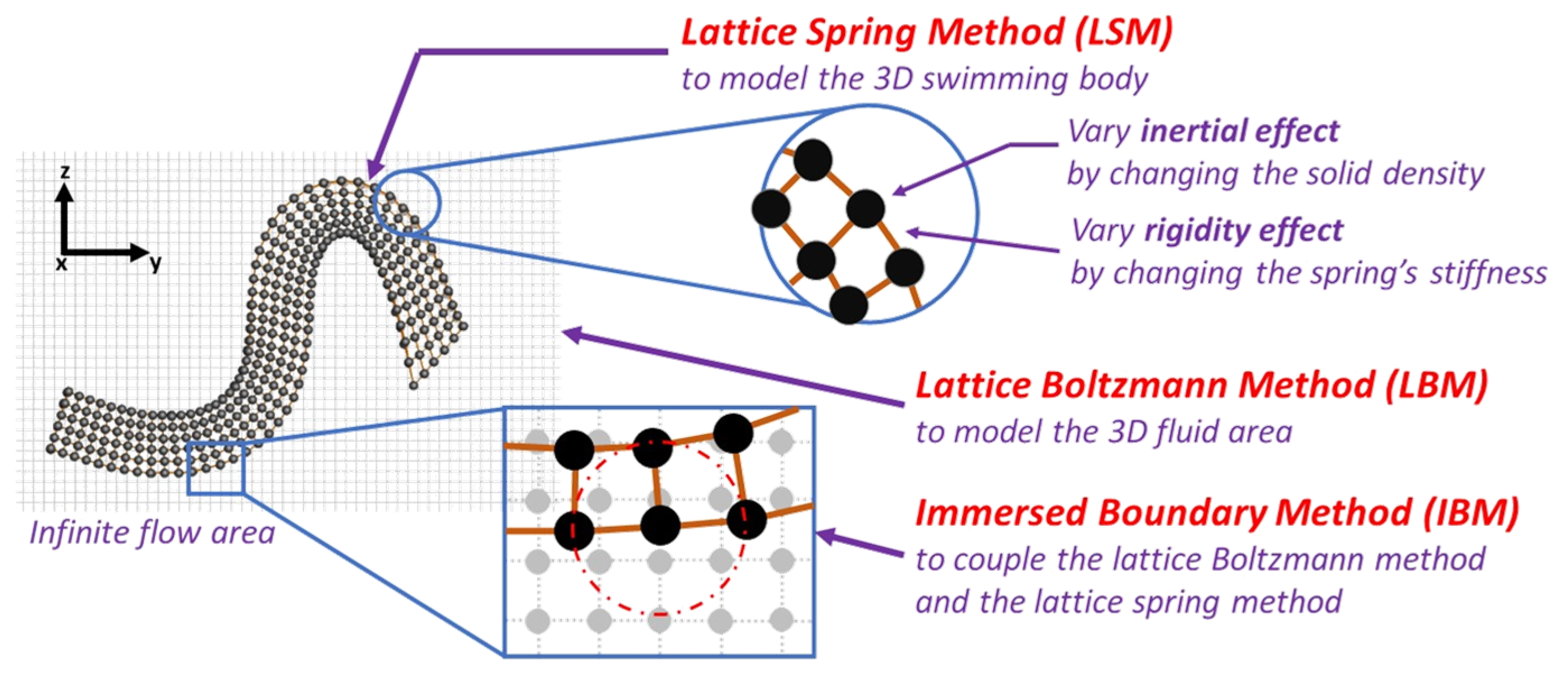

Fig. 4. The lattice Boltzmann method, lattice spring method, and immersed boundary method are numerical simulation methods we employ in this work.

Results

Flexibility on forward cruise

In the first portion, we only focus on the forward swimming. To evaluate the effect of the flexibility on the forward swimming performance, the average cruising speed as a function of rigidity is computed, as shown in the Fig. 5a. **The trend in this figure is that the speed increases as the rigidity increases, and the speed arrives at a global maximum at an intermediate rigidity. Then, the speed decreases as the rigidity continues to grow.**

Fig. 5b shows the average speed against the reduced frequency, i.e., the ratio of the driving frequency and natural frequency. The optimal swimming performance can be achieved when the driving frequency is close to the natural frequency. **This is known as resonance.**

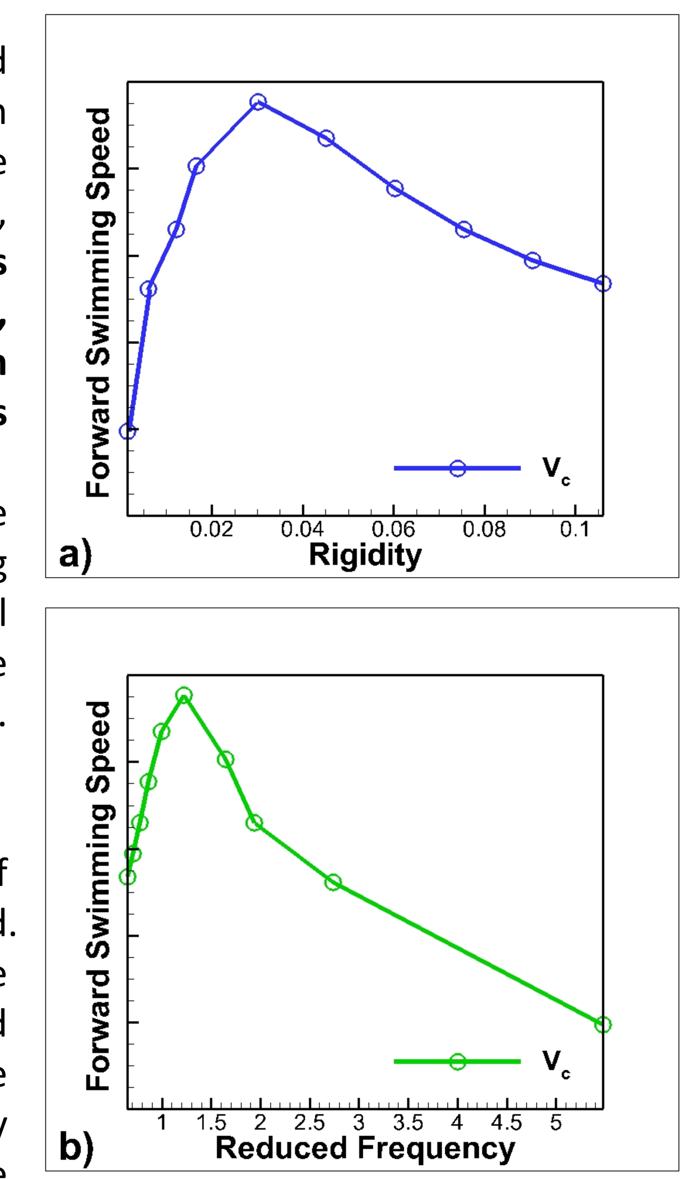

Fig. 5. The average cruising speed a) as a function of rigidity and b) as a function of the reduced frequency.

Cruise reversal and deformation

When the rigidity is large, the flapping motion of a slender swimmer propels itself swimming forward. However, as the rigidity continuously decreases, the swimmer may reverse its cruising direction and move backward (see Fig. 6). Deformations of the forward cruise and backward cruise are very different, as shown in Fig. 7. With a low rigidity, the swimmer body is very soft so that it deforms dramatically, resulting in a snake shaped body. **The different shapes affect hydrodynamic forces and fluid fields.**

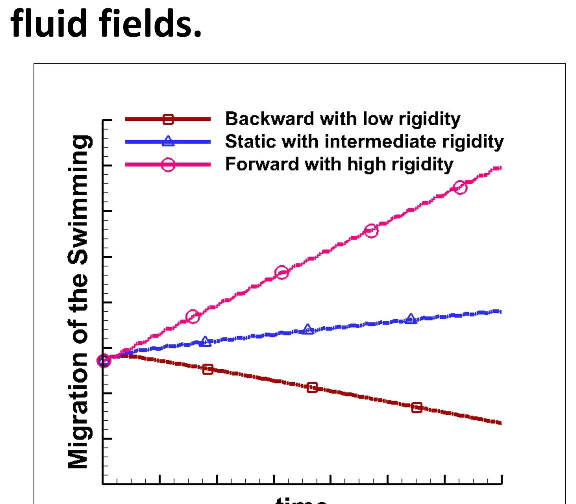

Fig. 6. The displacements in the cruising direction against time.

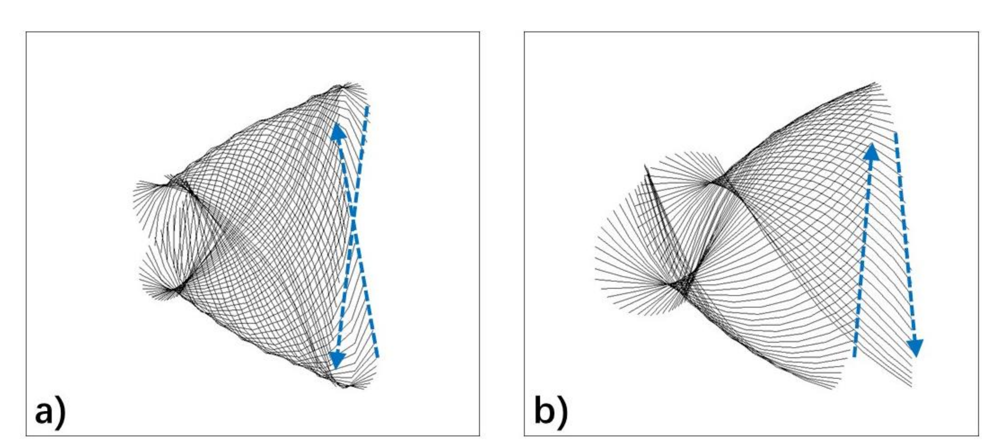

Fig. 7. The body deformation relative to the driving point is compared between a) the forward and b) backward cruise at different time instants (driving head moving with blue arrows).

Results (continue)

Fig. 8 explains how the hydrodynamic force pushes the body moving forward or backward. Fig. 9 explains the mechanism of the "sucking effect": the motion of the snake shaped body for the backward swimming induces two vortices located at both sides of the leading edge and the unbalanced effect of these two vertices produces a net backward force to drive the swimmer backward.

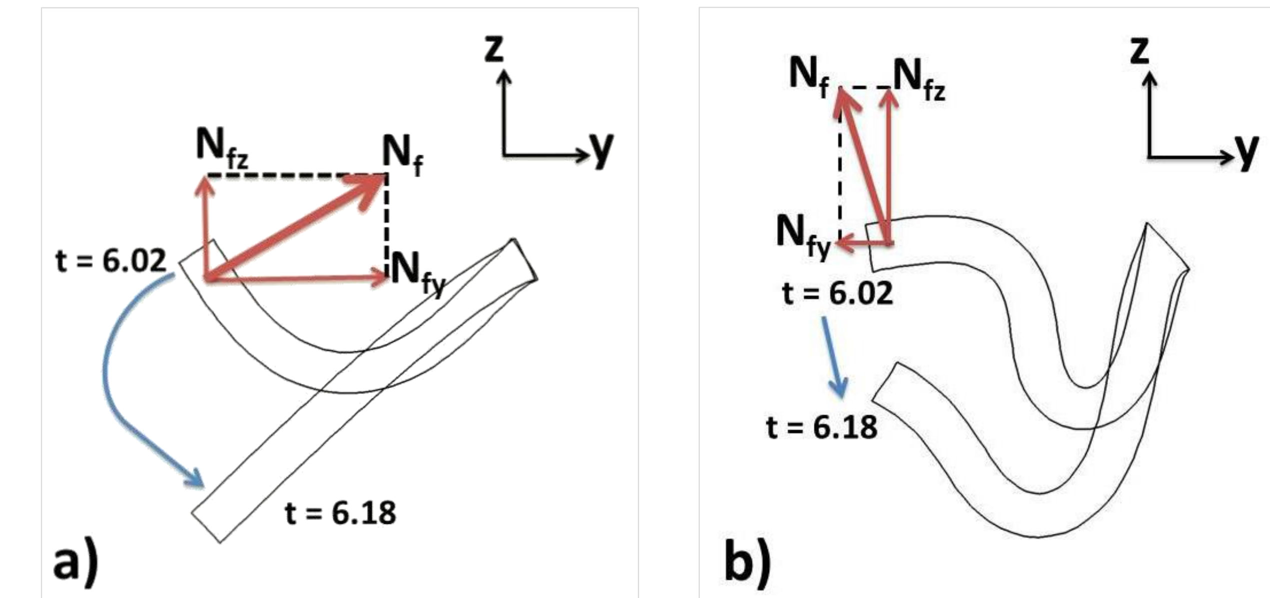

Fig. 8. Hydrodynamic forces working on the solid body for the a) forward cruise and b) backward cruise.

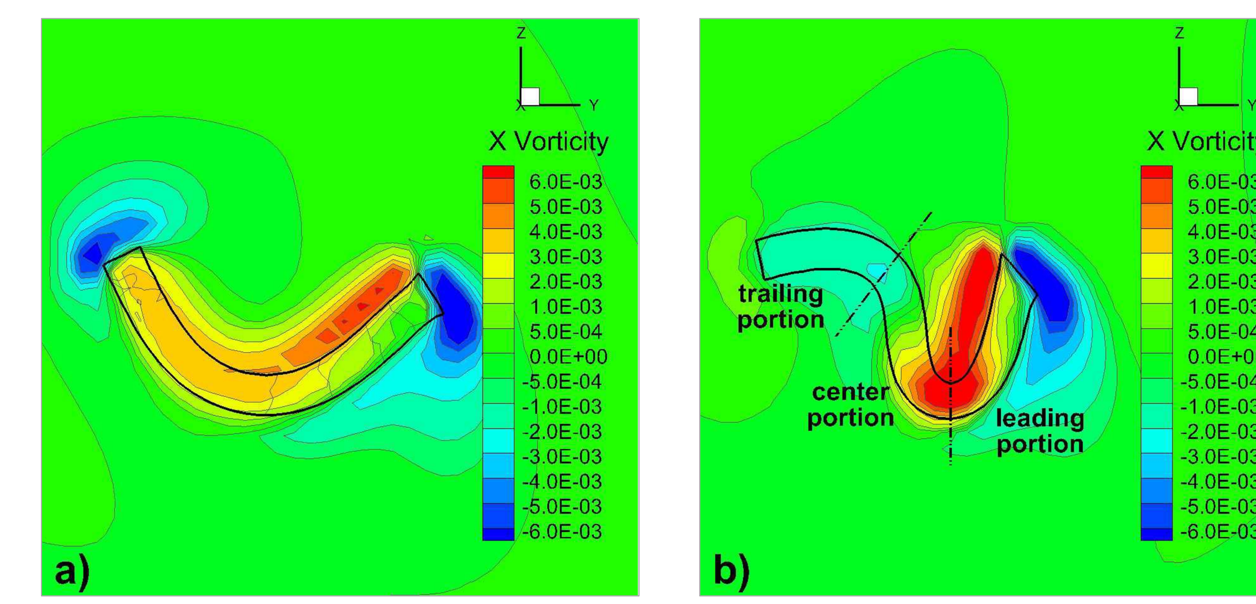

Fig. 9. The "sucking effect" a) does not occur for the forward movement and b) occurs for the backward movement.

Inertial effects on cruise reversal

According to the theory, an interplay among the inertia, elastic force, and hydrodynamic force determines the swimmer's motion and deformation. To investigate the influence of inertia, we vary inertia at different levels while other simulation conditions are kept the same. When the swimmers with low inertia, they move forward, as shown in Fig. 10 purple and red lines. As the inertia continuously increases to a specific level, the swimmer start to reverse its cursing direction, as shown in Fig. 10 blue and brown lines.

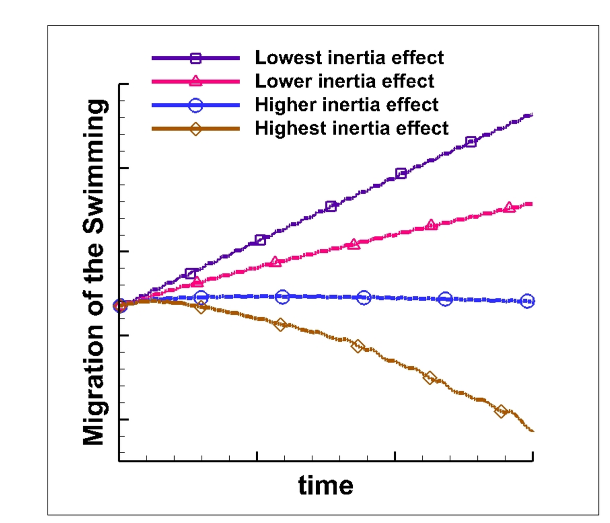

Fig. 10. The displacement as function of time are compared among the cases with different levels of effective inertia.

Conclusions

- Two cruise states (forward or backward) do exist and are can be manipulated by varying the swimmer's rigidity and inertia.
- The rigidity is systematically varied at different levels, and then the average cruising speed is computed. The optimal cruising performance do exist.
- The deformations of forward and backward movements are very different. The snake-like swimming body and the "sucking effect" of vortexes can explain the mechanism of the backward cruise.

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