Modeling and Characterization of Bacteria-inspired Bi-flagellated Mechanism with Tumbling

Zhuonan Hao[1]
Mechanical and Aerospace Engineering
University of California, Los Angeles
Los Angeles, USA
znhao@g.ucla.edu

Sangmin Lim[1]
Mechanical and Aerospace Engineering
University of California, Los Angeles
Los Angeles, USA
limsm3@g.ucla.edu

Mohammad Khalid Jawed[1]
Mechanical and Aerospace Engineering
University of California, Los Angeles
Los Angeles, USA
khalidjm@seas.ucla.edu

***Abstract*—We present a multi-flagellated robot [1] that can utilize the hydrodynamic interaction between their filamentary tails, known as flagella, to swim and change their swimming direction in low Reynolds number flow. Simplified hydrodynamics model, like Resistive Force Theories (RFT), lacks the capability to capture the dynamics of certain interactions known as bundling and tumbling. However, for the development of efficient and steerable robots inspired by bacteria, it becomes crucial to exploit this interaction. In this paper, we present the construction of a macroscopic bio-inspired robot featuring two rigid flagella arranged as right-handed helices, along with a cylindrical head. By rotating the flagella in opposite directions, the robot's body can reorient itself through repeatable and controllable tumbling. To accurately model this bi-flagellated mechanism in low Reynolds flow, we employ a coupling of rigid body dynamics and the method of Regularized Stokeslet Segments (RSS). Unlike RFT, RSS takes into account the hydrodynamic interaction between distant filamentary structures. Furthermore, we delve into the exploration of the parameter space in terms of the flagellum geometry to optimize the propulsion and torque of the system. To achieve the desired reorientation of the robot, we propose a tumble control scheme that involves modulating the rotation direction and speed of the two flagella. The scheme enhances the steerability by enabling the robot to attain the desired heading angle with high accuracy. Notably, the overall scheme boasts a simplified design and control as it only requires two control inputs. With our macroscopic framework serving as a foundation, we envision the eventual miniaturization of this technology to construct mobile and controllable micro-scale bacterial robots.**

***Index Terms*—bio-inspired robot, tumbling**

I. INTRODUCTION

The study of flagellated bacteria and microorganisms has provided valuable insights into the development of flagellated robots [2]–[4]. These robots mimic the locomotion of flagellated organisms, which rely on the intricate interaction between their helical structures, known as flagella, and the surrounding viscous fluid. By understanding and replicating these propulsion mechanisms, flagellated robots can achieve functional movements such as running, turning, and stopping. Additionally, natural observations have highlighted that different types of bacteria, including uni-flagellated and multi-flagellated species, rely on distinct propulsion mechanisms to achieve specific forms of locomotion [5], [6].

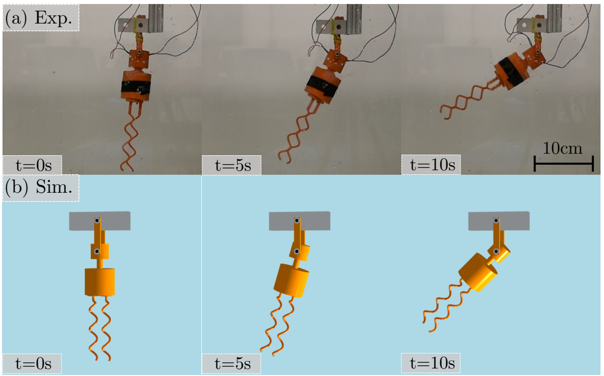

Fig. 1. Snapshots from (a) experiments and (b) simulations. Side view of the bi-flagellated rotating around an axis at $t \in \{0, 5, 10\}$s. Two identical flagella rotate in opposite directions, i.e., clockwise (CW) and counterclockwise (CCW), at an angular velocity of $\omega = 280$ rpm.

Multi-flagellated bacteria exhibit locomotion through the interplay of their flagella, involving phenomena such as bundle formation, tumbling, and polymorphic transformations, all of which arise from different flagella actuation [7]–[9]. Bundle formation occurs when two or more flagella spin in the same direction, generating efficient longitudinal propulsion. The propulsive force is approximately linearly related to the spin speed, and this observation has been effectively utilized in bi-flagellated robots to enable single-direction mobility [10], [11]. The presence of multiple flagella in these robots offers benefits, suggesting alternative approaches for speed enhancement beyond flagellum geometry optimization. However, a major limitation arises in the area of turning or reorienting the body, preventing these robots from swimming freely in space. Recent research has explored changing the spin direction of one or more flagella, gradually reducing the propulsion thrust and generating a turnover torque [5]. This results in rapid tumble events and seemingly erratic body reorientation. Our study models the tumbling event as a predictable phenomenon and aims to incorporate the tumbling mechanism into a bi-flagellated robot to enhance steerability.

The robot depicted in Figure 1 consists of a cylindrical head and two right-handed helical flagella with plates attached to the motor shaft. The head has a radius of r_h measuring 2.5 cm and a height of h measuring 4.3 cm. Inside the head, two tiny brushed DC geared motors are located, each rated at 6 V

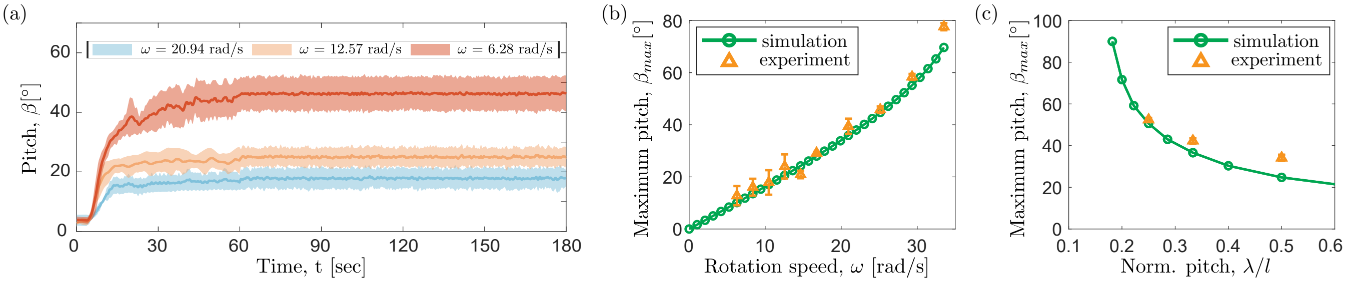

Fig. 2. Comparison of simulation and experiment for fixed-body rotation. (a) Time evolution of pitch angle β when angular speed of flagellum varying from 6.28 rad/s to 20.94 rad/s with $\lambda/l = 3, R/\lambda = 5, d/R = 3.5$. (b) The steady state values of pitch angle $\beta_{\max}$, as a function of angular velocity ω, with a parameter set: $\lambda/l = 3, R/\lambda = 5, d/R = 3.5$. (c) The steady state values of pitch angle $\beta_{\max}$, as a function of normalized radius R/λ, with a parameter set: $l/R = 15, d/R = 3.5$, and ω = 20.9 rad/s. (d) The steady state values of pitch angle $\beta_{\max}$, as a function of normalized pitch R/λ, with a parameter set: $R/\lambda = 5, d/R = 3.5$, and ω = 20.9 rad/s.

voltage and capable of a stall current of 1.5 A. The motors are equipped with magnetic encoders and an IMU module. The motor shaft protrudes from the head, and its rotation direction and speed are controlled via PWM feed using a microcontroller. The flagella are manufactured using rapid prototyping techniques with Polylactic acid (PLA), a type of 3D printing material. The PLA flagella have a fixed cross-sectional radius of r_0 measuring 1.58 mm and a helix radius R measuring 6.36 mm. To generate sufficient experimental data for investigating the tumbling mechanism, the helix length l is varied between 63.6 and 127.2 mm, while the helix pitch λ is varied between 15.9 and 63.6 mm. The PLA material used for the flagella is considered to be non-deformable, with Young's modulus E of 4.107×10^9 Pa. These design and parameter variations allow for the exploration of different configurations of the flagellated robot and provide a range of experimental data to study the underlying mechanisms of tumbling.

II. RESULTS

Toward validating the numerical simulations, we perform a direct quantitative comparison with experimental results using the apparatus described above. Emphases are given to the evolution of pitch angle β, as an accumulative result of applied forces and torques.

Firstly, we investigate how pitch angle β evolved with different flagellum parameters, including normalized pitch λ/l and rotation speed ω. In Figure 2(a), we plot β as a function of time t, with the reference assumed $\lambda/l = 3, R/\lambda = 5, d/R = 3.5$. The pitch angle keeps increasing with time and reaches a maximum value, denoted as $\beta_{\max}$. The magnitude of β_{max} is proportional to the rotation speed of the flagella. Therefore, though without measuring the value of turnover torque in the experiment, we can use the $\beta_{\max}$ as an indicator of torque magnitude. Figure 2 (b) plot the relationship between β_{ss} and rotation speed ω, and show an excellent agreement between experiments and simulations. We learn that the magnitude of torque generated by propulsion forces of two flagellum is linear with the rotation speed of the flagellum.

We lastly employ our numerical simulations to explore the effect of λ/l with a comparison with experiments when keeping the angular velocity of flagellum $\omega = 280$ rpm, for which we showed in the Figure 1 that there is a significant direction change effect. Figure 2(c) show a good match between the experiment and simulation of the tendency of $\beta_{\max}$ on λ/l.

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