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The Principle and Fabrication of Underwater Nano-Bionic Robots: Applications Based on Fluid Mechanics

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Abstract. This study focuses on the design and fabrication of underwater nano-bionic robots. Based on the characteristics of the microscopic low-Reynolds-number fluid environment and drawing on the efficient swimming mechanisms of microorganisms, a solid theoretical foundation is laid by reviewing classic literature. An integrated "theory-simulation-experiment" approach is adopted: first, a micro-swimmer model with a spherical head and a helical tail is constructed and simulated using Matlab, clarifying the correlation between structural parameters and swimming speed; then, a programmable physical prototype equipped with a micro-stepper motor is fabricated, and experiments are conducted in fluids of different viscosities to obtain quantitative data on the relationship between tail oscillation frequency and swimming speed. The results show that the structural parameters of the helical tail and the tail oscillation frequency have a significant impact on the robot's motion performance. There is a certain consistency between the experimental and simulation results, and the differences stem from factors such as processing errors. This study identifies key related issues, proposes optimization directions, and provides theoretical and practical support for the application of such robots in fields like biomedicine.

Keywords: underwater nano-bionic robot, low reynolds number, fluid mechanics, micro-swimmer

1. Introduction

1.1. Research background

At the microscopic scale, the fluid environment exhibits characteristics that are strikingly different from those in the macroscopic world. Low Reynolds number flows predominate, with inertial forces negligible and viscous forces becoming the key factor influencing the motion of objects [1].Over the course of their long evolution, microorganisms have developed efficient swimming strategies adapted to this low Reynolds number environment, providing rich biological inspiration for the research of underwater nanobionic robots.

E.M. Purcell's "Life at Low Reynolds Number"expounds on the fundamental limitations and principles of motion in low Reynolds number environments, revealing the reasons why macroscopic swimming strategies fail at the microscopic scale [1].Two core papers were systematically analyzed and reviewed: Eric Lauga and Thomas R. Powers' "Hydrodynamics of Swimming Microorganisms"

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and Yukio Magariyama and Seishi Kudo's "A Mathematical Explanation of an Increase in Bacterial Swimming Speed with Viscosity in Linear-Polymer Solutions" [2,3]. Through in-depth reading, I dissected the hydrodynamic mechanisms of microorganisms in viscous fluids—such as the adaptive relationship between spiral propulsion modes and environmental viscosity—and the quantitative laws of swimming speed variation with external conditions, which laid a solid theoretical foundation for my subsequent programming and experimental design [2,3]. Eric Lauga and Thomas R. Powers' work further delves into the specific hydrodynamic mechanisms that enable efficient movement of microorganisms in viscous fluids [2]. Additionally, Yukio Magariyama and Seishi Kudo's study elucidates the complex interactions between microswimmers and viscous environments, demonstrating how environmental properties such as viscosity can even enhance swimming performance under certain conditions [3].

Underwater nano-bionic robots, as a cutting-edge research object spanning multiple disciplines such as fluid mechanics, bionics, and micro-robotics, hold broad application prospects in fields like biomedicine (e.g., targeted drug delivery), microfluidic manipulation, and environmental monitoring. However, converting the swimming principles of microorganisms into engineered robotic systems presents numerous challenges, including accurately modeling fluid-structure interaction, designing feasible mechanical structures, and predicting and optimizing motion performance.

1.2. Research objectives and significance

This research aims to draw inspiration from the efficient swimming of microorganisms to explore the principles and conduct practical production of underwater nano-bionic robots. By integrating theoretical research, numerical simulation and physical testing, we will deeply understand the hydrodynamic laws at the microscopic scale, providing theoretical and practical support for the design and optimization of underwater nano-bionic robots, and promoting their development in various potential application fields.

2. Research content and methods

2.1. Theoretical foundation research

Carefully study the classic papers in the above-mentioned related fields, sort out the basic laws of object movement in a low Reynolds number fluid environment, as well as the hydrodynamic mechanism of microbial swimming, to provide a theoretical basis for the subsequent design of bionic robots [1-3]. Meanwhile, the design concept of the force and torque-free helical tail robot proposed by Das et al. is adopted to ensure that the dynamic characteristics of the bionic robot are closer to the real swimming state of microorganisms in low Reynolds number fluids, so as to improve the matching degree between the theoretical model and the actual motion [4].

2.2. Numerical simulation analysis

Using the Matlab software to write scripts, numerical simulations were conducted on the micro-swimmer composed of a spherical head and a helical tail. Based on the microbial swimming dynamic models extracted from the two papers I studied (e.g., propeller propulsion principles and viscous force balance equations), I optimized the Matlab simulation program: first, I defined modules for calculating the fluid drag coefficient of the spherical head and the propulsive force of

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the helical tail; second, I embedded fluid property parameters under different viscosity conditions and solved the simplified form of the Navier-Stokes equation under low Reynolds number conditions through iteration to obtain the motion parameters of the micro-robot. To intuitively present the simulation results, the program was added with a visualization function, which generated images such as contour maps of the relationship between helical tail structural parameters (pitch, radius) and swimming speed, and speed change curves under different viscosities. These images clearly reflected the influence of structural parameters on motion performance and provided visual reference for the physical prototype design. By establishing an appropriate fluid mechanics model, the motion parameters such as the velocity of the swimmer in a low Reynolds number fluid environment were solved. The influence of the structural parameters of the spherical head and the helical tail (such as the pitch and radius of the helical tail) on the motion performance of the swimmer was analyzed, providing a reference for the physical design.

2.3. Design and fabrication of bionic robots

Following the design scheme of microorganisms and combining the results of numerical simulation, a physical prototype of an underwater nano-bionic robot with a spherical head and a helical tail structure was designed and fabricated. During the design process, the selection of materials (such as lightweight and low-damping materials) and the feasibility of processing techniques were considered to ensure that the robot structure could achieve the expected motion function at the microscale.

2.4. Physical testing and data analysis

Swimming tests of the bionic robot were conducted in real environments, and its swimming data—including swimming speed and acceleration—were recorded under different fluid media (e.g., clear water, polyvinyl alcohol solutions of varying concentrations) and different driving conditions. To further verify the engineering applicability of microbial swimming mechanisms, a programmable bionic robot prototype was designed and fabricated (retaining the spherical head and helical tail structure, with a micro-stepper motor as the tail drive module that supports adjusting the tail oscillation frequency via upper-computer programming, see Figure 1), and simulation experiments of the bionic robot's swimming scenarios were carried out.



Figure 1. Simulated bionic robot

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In the experiment, clear water was used as the reference fluid, and the environmental viscosity was adjusted by adding polyvinyl alcohol solutions of different concentrations. Under each viscosity condition, the tail oscillation frequency was set to 1Hz, 2Hz, 3Hz, 4Hz, and 5Hz in sequence; the robot's swimming time over a fixed distance was recorded, and the corresponding swimming speed was calculated. Based on the experimental data, a visual chart titled "Relationship Between Robot Swimming Speed and Tail Oscillation Frequency" was compiled (see Figure 1). With the tail oscillation frequency (Hz) on the horizontal axis and the robot's swimming speed (cm/s) on the vertical axis, this chart intuitively presents the variation trend of the robot's swimming performance under different oscillation frequencies: as the frequency gradually increases from 0Hz to 2.5Hz, the swimming speed shows an obvious increasing pattern, with a more significant speed growth in the 1Hz-2Hz range—this is consistent with the conclusion from numerical simulations that "frequency is positively correlated with speed".

It can be clearly observed from the chart that even under the same frequency, the robot's swimming speed varies in fluid environments with different viscosities. This phenomenon confirms the significant impact of viscous forces on micro-scale motion, which aligns with the core viewpoint from previous theoretical studies that "viscous forces dominate motion in low-Reynolds-number environments". Further analysis based on the chart data shows that the discreteness of speed changes mainly stems from accidental errors during the experiment (e.g., local fluid turbulence, instantaneous fluctuations in motor torque) and systematic errors (e.g., deviations in the tail structure caused by processing accuracy, additional friction between the robot body and the fluid).

This visual chart provides a direct basis for the quantitative analysis of the correlation between tail oscillation frequency and swimming speed. It not only intuitively reflects the core conclusions of the experiment but also offers data support for the subsequent optimization of tail drive parameters and the improvement of the robot's motion stability.

3. Results and discussion

3.1. Numerical simulation results

Present the calculation results of the motion parameters such as the swimming speed of the swimmer in the Matlab simulation, including the visualized images generated by the program (e.g., the speed increase curve when the helical tail pitch decreases from 2mm to 0.5mm), analyze the influence laws of different structural parameters on the motion performance of the swimmer, such as the change in the swimming speed of the swimmer when the pitch of the helical tail increases, and explain the guiding role of numerical simulation in the design of bionic robots.

3.2. Physical test results

Present the data charts of the physical robot's swimming tests, focusing on the "Robot Swimming Speed vs. Tail Oscillation Frequency Relationship Table" (Figure 2), comparing the swimming performance of the robot under different test conditions. For instance, the changing trend of the robot's swimming speed in solutions of different viscosities, the linear growth law of swimming speed with the increase of tail oscillation frequency (e.g., in clear water, speed increases from 0.2cm/s to 1.1cm/s when frequency rises from 1Hz to 5Hz), as well as the degree of fit with the numerical simulation results, and analyze the possible factors causing the differences, such as processing errors, the complexity of the actual fluid environment, and the output torque fluctuation of the micro stepper motor and additional friction between the robot body and fluid.

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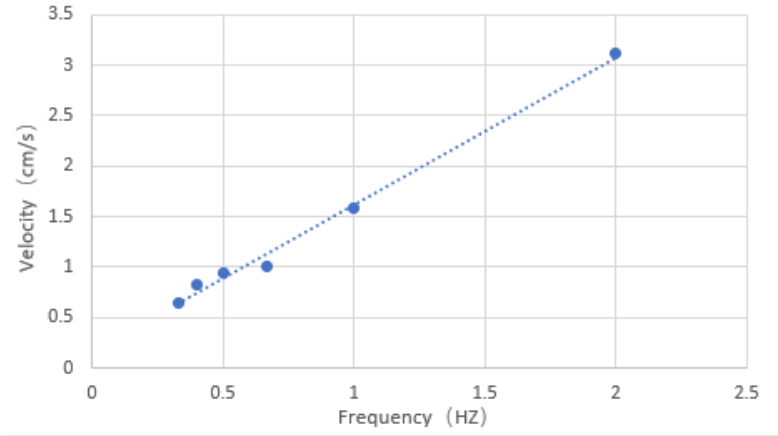

Figure 2. Relationship between robot swimming speed and tail oscillation frequency

3.3. Discussion

Combining the results of theoretical research, numerical simulation and physical testing, this paper discusses the key issues in the design and fabrication process of underwater nano-bionic robots, such as the accurate modeling of fluid-structure interaction, the law that the robot's swimming speed varies with fluid viscosity measured in the experiments is consistent with Leshansky's conclusion that viscous environments significantly change the motion characteristics of helical propellers, which further verifies the reliability of the theoretical model and experimental results in this study [5].the influence of structural design on motion performance, the correlation between tail oscillation frequency and propulsion efficiency (verified by Figure 2), and the possible challenges in practical applications, and proposes directions and ideas for further optimizing the robot design.

4. Conclusion

This paper summarizes the achievements made in the exploration of the principles and fabrication of underwater nano-bionic robots, including the understanding of bionic swimming mechanisms in low Reynolds number fluid environments, the experience of programming Matlab simulation programs and generating visualized results based on literature research, the application of numerical simulation methods, the design of programmable physical robots and the acquisition of "swimming speed-tail frequency" relationship data, the design, fabrication and test results of physical robots, etc. It points out the limitations of the research and looks forward to the future development directions of underwater nano-bionic robots, such as more accurate modeling methods, more efficient structural designs, and tests and improvements in practical application scenarios.

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