NANO BIONIC SWIMMING ROBOTICS AND APPLICATIONS IN ENVIRONMENTAL ENGINEERING

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ABSTRACT

As microscopic swimmers survive in nature, they have evolved unique structures and swimming patterns under the water, which has special advantages. The movement of bacteria at low Reynolds number (Re) environment has aroused extensive research interest. The two typical swimming methods of bacteria are introduced in this paper.

Based on this, we are inspired to design the bionic robot on a micro-scale, which is an artificial structure that imitates the external shape, movement principle and behavior mode of organisms in nature. Compared with traditional robots, nano bionic robots are easier to miniaturize[1]. They also have higher maneuverability so that they can move continuously and flexibly. We expect to simulate its motion at low Reynolds number (Re) fluids and explore complex future applications in different fields.

KEYWORDS

Microscopic swimmers, Low Re, Bionic robots, Applications

1. INTRODUCTION

1.1. Background and Goals

The Nobel Prize winner Richard Feynman puts forward the concept of nano bionic robots. It is based on the biological principle at the molecular level as the prototype to design a "molecular device" that can operate in the nano space, also known as the molecular robot[2]. Nano robot is the most attractive content of biomedicine, and the extreme environment is its main working environment.

Some major applications of nano bionic robots will be widely implemented in a variety of fields, from information technology to biotechnology, from medicine to aerospace and so on. Nowadays, a number of previous research projects have explored the use of nano bionic robotics in the medical field[3]. Those tiny nanoparticles have the ability to change the body's dynamics with minimal side effects, allowing them to perform specific tasks inside the body, including the development of the nano robot assisted fertilization and the nano spider robot composed of DNA molecules that move along membrane surface [4][5]. However, they are still in the research and development stage, and some technical barriers remain to be solved. We are inspired by the previous research and try to design the artificial nano bionic robot in order to apply it to the wastewater control technology in the field of environmental engineering in this paper.

Fluid mechanics plays an important role in Environmental Engineering. In this field, we study the static/ dynamic state of the fluid itself as well as the interaction when the fluid and solid boundary are in relative motion under various forces. Here we introduce the definition of Reynolds number (Re), a similarity criterion constant in fluid mechanics to characterize the influence of viscosity, which is defined as the ratio of the inertial forces to the viscous forces.

$$Re = \frac{Inertialforces}{Viscousforces} = \frac{av\rho}{\eta} = \frac{av}{v} \quad (1)$$

Where：ρ and η: density and viscosity of the fluid;
ν: kinematic viscosity, $\nu = 10^{-2} \mathrm{cm}^2/\mathrm{sec}$ (for water);
a: dimension.

People, fish, and microbes, also swim in water, but the physical behavior and Re numbers of various creatures are also quite different because of the huge differences in length scales. The Renumber for a man swimming in a liquid may be 10^4. However, when it comes to the microbial world, the Re number for the animals that we're going to be talking about may get down to only 10^{-4}or 10^{-5}.

Normally, the force is proportional to the acceleration, but when the Re number is extremely low, the viscous forces dominate, which means inertial force plays no role and the force is proportional to the velocity only. We aim to find out why swimming at the micro-scaleis so difficult and then try to design an artificial nano robot that can overcome the difficulties when they swim at a low-Re number.

In summary, the objectives of the research were:
(1) Studying the physics of swimming problems at low-Re numbers;
(2) Designing the artificial micro-swimmer based on the theory part by analyzing, programming, modeling, etc.;
Discussingfuture prospects of Nano Bionic Swimming Robotics.

2. THEORY AND METHOD

2.1. Scallop Theorem

The most significant difference in microbial movement is the reversibility in time, that is, any motion is the result of the forces that are exerted on them currently and has nothing to do with the past at a low Re number. Under this circumstance, we can even move backward by exerting reverse forces. This makes it clear what a low Re number implies. Imagining scallops, they swim by the shock of slowly opening their shells in the water and then quickly closing them together. Finding that they have been doing reciprocating motion and the shells open and close symmetrically in time, so they cannot swim at a low Re number unluckily[6]. Only if microbes break time reversibility, can they swim at a low Re number. This is what we called the Scallop Theorem. Based on this, we will explore how bacteria with micro-scale swim in a liquid environment.

According to E.M. Purcell, an American physicist who shared, with Felix Bloch of the United States, the Nobel Prize for Physics in 1952, there are two main methods to the problem of swimming in the microbe world[6]. One way we may call flexible oar (fig.1), the fluttering of their flexible flagella, like sperm. Another one might be a corkscrew (fig.1), rotating their helical flagella filaments and helical cell bodies[6]. For example, the most common E. coli rotates its flagella like a screw, and other microorganisms have their own special structures to meet their swimming needs.

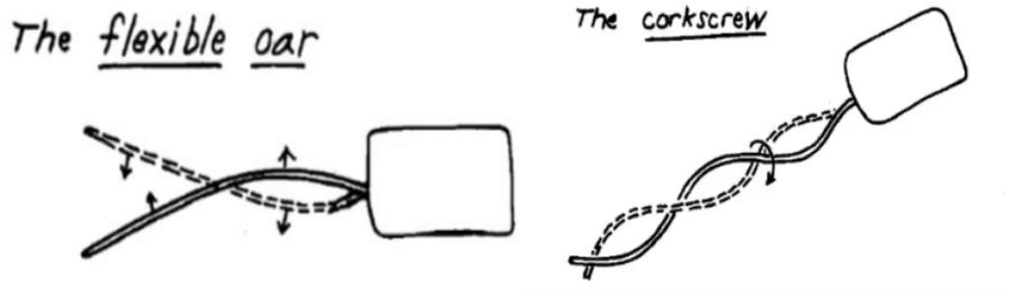

Figure 1. Solutions to the problem of swimming at a low Re number[6]

In the following part, we are going to talk about how a rotating corkscrew propels something first. Remember everything is linear at a low Re number, so we see matrices come in.

2.2. Matrix Method

For low-Re number swimmer:
F=Av+BΩ (2)
N=Cv+DΩ (3)
Here we regard this matrix as a propulsion matrix, known as its elements A, B, C and D, which is applicable to the motion of any shape of the object at a low Re number. The respective number of A, B, C and D depends on the shape of the object. The total matrix of the system can be equal to the sum of each individual in a series.

We aim to develop a mathematical explanation of bacterial swimming speed with viscosity in linear-polymer solutions, therefore the traditional hydrodynamic solutions do not apply to the motion of microorganisms in solutions containing viscous components[7]. Here we see a mathematical expression of force theory comes in.

2.3. Mathematical Expression of Force Theory

Equations of motion.

$$F_c + F_f = 0 \tag{4}$$
$$T_c + T_f = 0 \tag{5}$$

Where：F_c and T_c: Hydrodynamic force and torque acting on cell body;
F_f and T_f: Hydrodynamic force and torque acting on flagella filament;
Drag force and torque act on a cell body.

$$F_c = \alpha_c \tag{6}$$
$$T_c = \beta_c \omega_c \tag{7}$$

Where:α_c and β_c: Drag coefficients of cell body;
ω_c: Rotation rates of cell body;
V: Swimming speed;
Drag force and torque on a flagella filament.

$$F_f = \gamma_f v + \beta_f \omega_f \quad (8)$$

$$F_f = \gamma_f v + \beta_f \omega_f \quad (9)$$

where：α_f , β_f and γ_f: Drag coefficients of flagella filament;
ω_f: Rotation rates of flagella filament.
Drag coefficients α_c, β_c; α_f , β_f and γ_f were written as follows[8]:

$$\alpha_c = -6\pi\mu a\left\{1-\frac{1}{5}\left(1-\frac{b}{a}\right)\right\} \quad (10)$$

$$\beta_c = -8\pi\mu a^3\left\{1-\frac{3}{5}\left(1-\frac{b}{a}\right)\right\} \quad (11)$$

$$\alpha_f = \frac{2\pi\mu L}{\left[ln\left(\frac{d}{2p}\right)+\frac{1}{2}\right](4\pi^2r^2+p^2)}(8\pi^2r^2+p^2) \quad (12)$$

$$\beta_f = \frac{2\pi\mu L}{\left[ln\left(\frac{d}{2p}\right)+\frac{1}{2}\right](4\pi^2r^2+p^2)}(4\pi^2r^2+2p^2)r^2 \quad (13)$$

$$\gamma_f = \frac{2\pi\mu L}{\left[ln\left(\frac{d}{2p}\right)+\frac{1}{2}\right](4\pi^2r^2+p^2)}(-2\pi^2r^2p) \quad (14)$$

Where：μ: Viscosity, $\mu = 0.8973 \times 10^{-3}$pa. s (under 25℃);
2a, 2b: Cell width and cell length;
2d: Diameter of flagella filament;
L: Length of flagella filament.;
R: Radius of flagella filament;
P: pitch angle, $\tan[\theta] = \frac{p}{2\pi r}$.

3. Results

3.1. Programming Part

Our purpose is to implement the theory by programming method. So here we use Matlab to program the calculations mentioned above. The known micro swimmer（fig.2）, as an example:

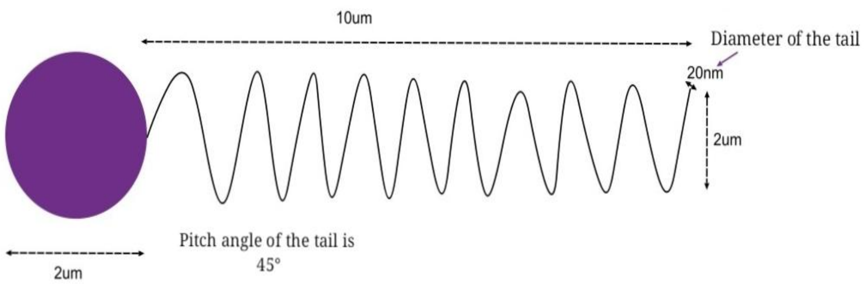

Figure 2. The schematic of the example

The relation between velocity versus pitch angle is shown in the figure below (fig.3). When the pitch angle changes from 0 to $\frac{\pi}{4}$, the velocity increases with the increase of the pitch angle and reaches the maximum value at $\frac{\pi}{4}$. When pitch angle changes from $\frac{\pi}{4}$ to $\frac{\pi}{2}$, the velocity decreases with the change of the pitch angle

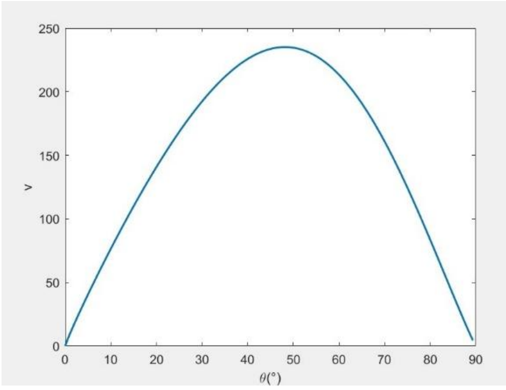

Figure 3. The plot of velocity versus pitch angle

After this work, we still use Matlab to simulate the swimming process of an E. coli with 2D, which swims following a run-and-tumble process. Knowing the run speed of E. coli is 25μm/s, the average run time is 1s and follows an exponential distribution, average tumble time is 0.1s, which also follows an exponential distribution. In short, there is a tumble event between two run events in the swimming process of E. coli. Using two random arrays for run and tumble to plot the speed vs time as well as the Vy vs Vx (add white noises language). From this work, we finally plotted the swimming trajectory with 2D. The results (random) are as followed (fig.4-fig.6):

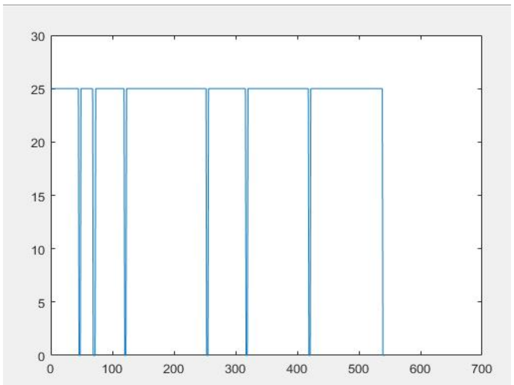

Figure 4. The plot between speed (um/s) versus Time (s)

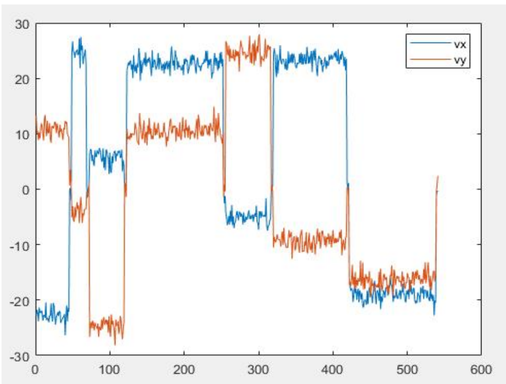

Figure 5. The plot between Vy (um/s) versus Vx (um/s)

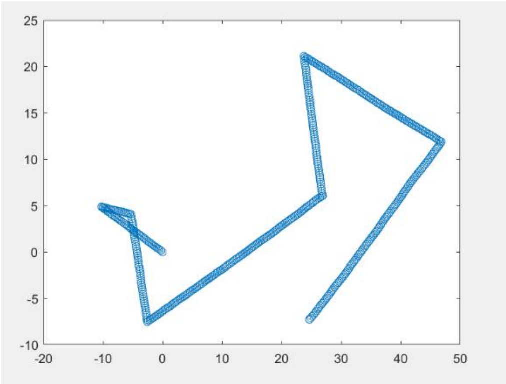

Figure 6. The plot between Y (um) versus X (um)

Based on all the work mentioned above, we finally come to the most challenging but interesting part, the design of artificial micro-swimmers, which is also known as bionic swimming robotics design. Two of the most common models for doing this are 3D printouts and 3D modeling to simulate the animation of its trajectory. Here we are going to talk about the way of 3D modeling.

3.2. Modeling Part

Using Pro engineering to Model E. coli in 3D (fig.7), the cilium on its cell body and its flagella should be flexible, but Pro engineering cannot manage as vivid as the real thing. Then, based on the plot of Y vs X drawn by Matlab, we could simulate its swimming trajectory as is shown in the video . The screenshot of its swimming trajectory in the video is shown below (fig.8). The cell body rotates in the opposite direction to the flagellum, and the difference in speed should be large even though it is not obvious in the video.

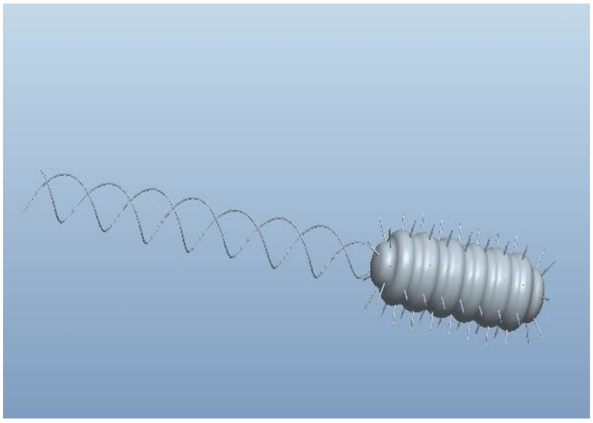

Figure 7. The 3D modeling of E. coli

Please check this link at https://youtu.be/W-lNw1iWHU4 for your convenience.

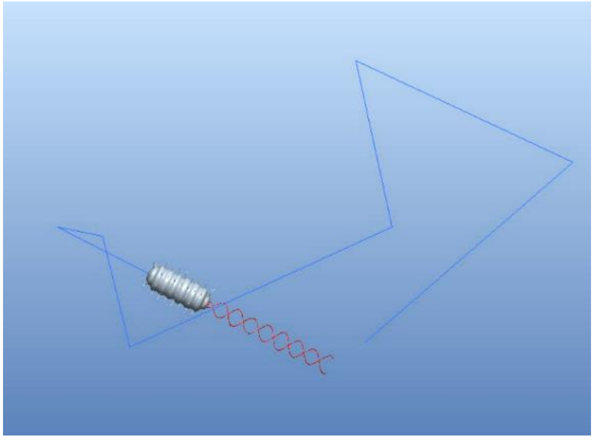

Figure 8. Swimming trajectory of E. coli modeled by Pro Engineering

4. DISCUSSION

4.1. Nanotechnology and Nano Bionic Robotics

With the development of technology, nano-scale substances are widely used in human life. Nanotechnology turns underwater bionic robots to enter a flexible era instead of the traditional rigid era. We intend to design a nano bionic robot by using E. coli as a model in this paper. The combination of these two enables the nano bionic robot to move continuously and flexibly, better mimicking the movement of bacteria at low Re number fluids.

4.2. Prospects of Nano Bionic Robotics in Wastewater Treatment Engineering

Generally speaking, there are two kinds of water pollution sources: human factors and natural factors. Water pollution caused by human activities accounts for two-thirds of the total due to the development of urbanization and Industry. Urban and industrial wastewater is a serious threat to the ecological environment, so it is very important to accurately monitor and quickly target the pollutants in polluted water bodies. We are inspired to apply nano bionic robots to wastewater control engineering, which do not need to have extremely complicated structures but need to have the ability to receive radio wave signals. They can still move around as well as monitor contaminants in poor condition fluids without creating additional pollution by self-propelling, just like those microscopic swimmers in nature. By conveying the information they detect to the nearest robot through radio waves, the detection information will be transmitted to the central control system in the end. In this way, The bionic robot only acts as a medium for information transmission, so that we are able to treat polluted water bodies quickly.

4.3. Improvement and Innovation

The future development trend of nano bionic robots using in wastewater control engineering will be more flexible, efficient, stable, and will be applied to more aspects of the wastewater treatment process. Currently, wastewater testing mainly uses the sampling method, then is analyzed in the laboratory, which is still mainly based on chemical agents for a variety of experimental data comparisons. Therefore, the process is generally complex, time-consuming, and not flexible enough. However, the new technology supports the collection and analysis of data directly, especially in extremely viscous fluid bodies, offering the advantages of faster calculations, reducing device requirements, and allowing for remote control as well.

In addition to obtaining inspiration from the physical characteristics and propulsion of the creature, it is also necessary to emphasize the self-perception, self-control and other performance characteristics, positioning in the water and environmental perception for example, much closer to the micro creatures in nature[9][10][11].

However, due to the complexity of the wastewater environment, the material requirements of nano bionic robotics are very strict, we may have to add antibodies to their surfaces to prevent them from being eroded by contaminants.

Finally, considering they are nano-scale devices, their computing power is still limited. Therefore, our aim is to reduce their manufacturing costs and produce them on a large scale in order to let them work together. On this basis, we then need to establish a complete information transmission system, which can be controlled by a small programmable logic controller (PLC) that can detect various parameters instantly and adjust the operation status of each part automatically. Once this design is successful, it will bring a great breakthrough in the fight against water pollution. However further research is still needed to pursue sustainability along the way to make this technology more mature.

As for the innovation, I think we may study the bionic robot with two tails and the rotation of two tails, arranged at each end of the robot body. I think the design enables the robot to have multiple degrees of freedom such as forward, backward and turning. By optimizing the structure of the spiral tail, the shape of the robot body and the distance between the two spiral tails, in order to achieve good performance. We may figure it out in the future research work.

5. CONCLUSION

In this paper, E. coli was used as the model of a nano bionic swimming robot to analyze each characteristic value of the artificial nano bionic robot by programming, and the final result was presented by modeling animation. In conclusion, the following points need to be highlighted:

(1)The overall design is based on the physics of micro-organism swimming mechanisms at low-Re number;
(2)When the pitch angle of the tail is about 45 degrees, its swimming speed reaches the maximum;
(3)The whole process follows a run-and-tumble process. We programmed it with random arrays, the pattern shown above is just one of those random cases;
(4)In order to put the design into practice, we discussed the possibility of using nano bionic swimming robots in sewage treatment engineering.

In the twenty-first century, research in the fields of nanotechnology, biology and environmental engineering should be developed in conjunction with social development. In this way, we can get a deeper understanding of the integrate field and put forward more innovative ideas, so as to always have hope for a “artificial nano bionic robotics revolution” in the future.

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Treatment Engineering. My gratitude also goes to everyone who helped me, shared with me my worries and was always be patient with me.

True talents always shine through. I will always cherish this valuable experience as it led me into a challenging yet fascinating field of academic research, which was, is and will be of great significant to my whole studying life.

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