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# Simulation Study on Serpentine Locomotion of Underwater Snake-like Robot

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### Abstract

*Serpentine locomotion of underwater snake-like robot is very complicated. In order to better control the motion state, a simulation model of underwater snake-like robot is established to investigate the relationship between the motion performance and the mechanical structure characteristics together with serpentine gait parameters. Based on the density ratio defined as the ratio of snake-like robot density to water density, the locomotion speed, output power and energy consumption of underwater snake-like robot is discussed. Further, with the optimum density ratio, the influence of serpentine gait parameters on the locomotion speed is analyzed. The simulation results show that the density ratio has great influence on the motion performance and the energy consumption of underwater snake-like robot, which can provide important basis for the research of underwater snake-like robot in terms of motion performance optimization and mechanical structure design.*

***Keywords:*** *Snake-like robot, Density ratio, Gait parameters, Motion performance, Simulation*

## 1. Introduction

Robot movement and control are confronted with great challenges in the unstructured environment such as marsh, liquid and loose surface. But biological snakes are able to adapt to such environment and to motion with ease. Imitating the real snake body structure, the snake-like robot came into being. Snake-like robot is an important branch of the robot research field, and many different models have been proposed [1-3]. Compared to the traditional snake-like robot, amphibious snake-like robot has the advantage of aquatic environment adaptability [4-6]. However, few such prototypes have been developed.

In the design of the underwater snake-like robot, the chain tandem structure is adopted to establish the relevant model, and it is further simplified as the multi-connecting-rod tandem structure used for dynamic analysis [7-10]. The underwater snake-like robot and the flow field around are distributed. When making the analysis of the underwater locomotion of a snake-like robot in dynamics, the coupling of the fluids and the solids is very difficult to simulate [11]. In general, the dynamic analysis of underwater snake-like robot is aiming at the joint modules based on simplified principles [9, 12]. In addition, the various gait parameters have different impacts on the motion performance of underwater snake-like robot [5, 13]. Ref. [11] simulates all the gait parameters of serpentine locomotion of underwater snake-like robot, and analyzes the influence of the gait parameters on the velocity. In the current studies on locomotion simulation of underwater snake-like robot, only the various gait parameters related to the motion performance are considered, while the effects of mechanical structure characteristics of underwater snake-like robot itself on the motion performance are ignored. When a snake-like robot is not completely submerged in water, this research method for analyzing the motion

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performance of underwater snake-like robot has some limitations.

The hydrodynamic force on underwater snake-like robot is mainly including the added mass force and the drag resistance, where the magnitude of the added mass force is directly proportional to the effective volume of a snake-like robot submerged in water, and the magnitude of the drag resistance is related to the effective cross-sectional area of underwater snake-like robot. The size of the effective volume and the effective cross-sectional area are determined by the ratio of the density of a snake-like robot relative to the water. In our simulation model we define the ratio as the density ratio. The density ratio affects the position, orientation, effective volume, and effective cross-sectional area of underwater snake-like robot to a certain degree, which further determines the force status of underwater snake-like robot. Therefore, the influence of the density ratio on the motion performance of underwater snake-like robot can't be ignored.

In addition, good design for underwater snake-like robot should also take into account other factors such as buoyancy and gravity, and let the buoyancy nearly equal the gravity. But once the physical model changes, the value of the density ratio will be changed, and the balance of the buoyancy and gravity is broken and needs to re-establish.

Based on the above reasons, this paper first analyzes the effect of different density ratio on the locomotion speed, output power and energy consumption of underwater snake-like robot by the simulation experiments. Further, the effect of serpentine locomotion gait parameters on the locomotion performance of underwater snake-like robot is discussed with the optimal value of the density ratio.

The paper is organized as follows. The simulation system is first presented in Section 2. Further, the model of underwater snake-like robot is established in Section 3. On this basis, the simulation analysis is studied in terms of the density ratio and the serpentine gait parameters of underwater snake-like robot in Section 4. Finally, the conclusions of simulation results are given in Section 5.

## 2. Construction of Simulation Systems

The simulation system block diagram of underwater snake-like robot is shown in Figure 1. Three parts were considered in the simulation system including the analysis of basic model, the construction of simulation platform, and the post-processing. Next, we give the description as follows.

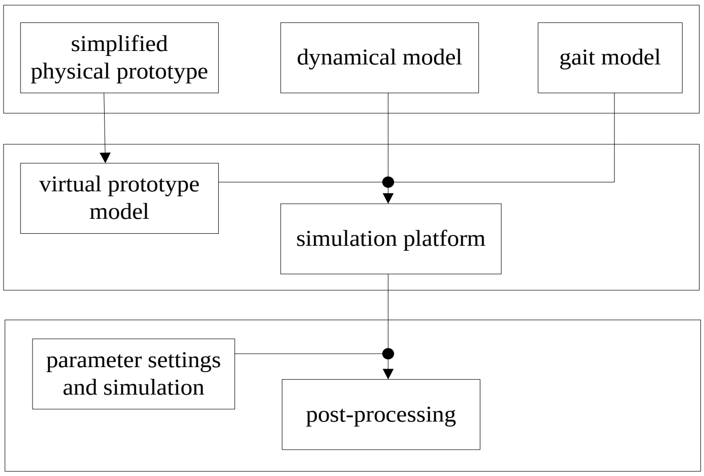


**Figure 1. The Simulation System Diagram of Underwater Snake-like Robot**

1) The basic model

The basic model consists of simplified physical prototype, the construction of dynamical model, and the construction of gait model, which analyzes the mechanical structure characteristics and the force status to control underwater snake-like robot serpentine locomotion.

The simplified physical prototype is built with the basic structural parameters and the connection mode between the joints of underwater snake-like robot. The dynamical model is established according to the external force that a snake-like robot is subject to in water, and it can simulate the real force status of underwater snake-like robot as accurately as possible. The gait model aims at controlling all the joints of underwater snake-like robot with an orderly motion to simulate all kinds of motions that a biological snake has.

2) The simulation platform

The basic model provides the theoretical basis for the construction of the simulation platform. Based on the connection mode between joints and the size structure of the simplified model attained from the physical prototype of underwater snake-like robot, a virtual prototype model can be built. Adding the dynamical model and the gait model to the virtual prototype model constitutes a simulation platform. The construction of the virtual prototype model and the simulation platform makes use of the dynamics simulation software ADAMS.

3) The post-processing

This part is mainly to control simulation output of simulation platform or to further process the simulation results in order to get the relationship between the output and other parameters.

## 3. Construction of Underwater Snake-like Robot Model

### 3.1. Construction of Virtual Prototype Model

The biological snake spine consists of a skull and a large number of ribs and spines. Each spine is very similar in structure, and its physiological function is also very similar. Each spine has a certain range of motion, and the tiny movement of adjacent spines superimposed together can make snake body configuration changing. A series of regular movement of some or all of the spines can make a snake form specific movement.

Based on the body structure and motion characteristic of nature biology snake, the underwater snake-like robot can be designed using limited modular joints with increasing movement space [14]. Each joint module has the same mechanical structure and the same degree of freedom. When entering the same control information, the modular joints will produce the same movement.

A limited number of joint modules with larger motion space linking in series can form the main body of underwater snake-like robot. Under the control of a series of regular discretization information, the underwater snake-like robot can achieve the motions that a biological snake has.

The schematic diagram of the joint module of underwater snake-like robot is shown in figure 2. The joint module consists of main body and the space motion parts. The main body of the joint module is equivalent to a homogeneous symmetric cylinder. The motion function of the joint module is similar to the gimbal mechanism with two rotational degrees of freedom of pitch and yaw except the head joint module. The joint modules can achieve the 3D movement by the superposition of two rotational degrees of freedom. The overall structure of underwater snake-like robot is shown in figure 3, which consists of nine joint modules in series. Body and pitch as well as pitch and yaw are connected via a revolute joint. The previous body and the next yaw are connected via a fixed joint. The pitch degrees of freedom of all the joints are in the same plane, so are the yaw degrees of freedom, and the two planes are vertical.

 

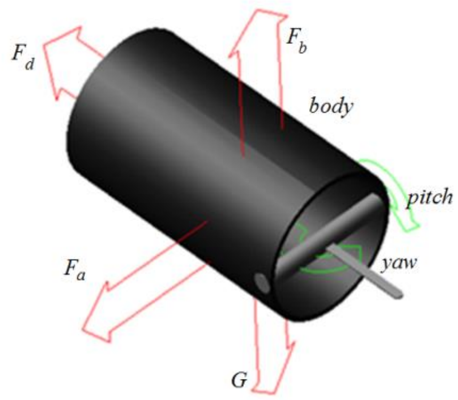


**Figure 2. The Schematic Diagram of a Joint Module**

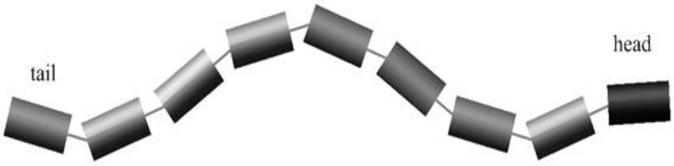


**Figure 3. The View of Underwater Snake-like Robot**

### 3.2. Construction of Dynamic Model

A snake-like robot moving in water is mainly subject to gravity, buoyancy, and hydrodynamic force. Next, the analysis of buoyancy and hydrodynamic force are given, respectively.

**3.2.1. Analysis of Buoyancy:** The magnitude of buoyancy of underwater snake-like robot is directly proportional to the weight of displaced water. When a snake-like robot is wholly or partially immersed in water, the buoyancy acts through the center of buoyancy of immersed snake-like robot. For a homogeneous symmetric joint module, the center of buoyancy is the center of mass [15]. But, the center of buoyancy is not fixed because the position and the orientation of underwater snake-like robot are constantly changing.

The buoyancy $F_b$ on underwater snake-like robot can be defined as Eq. (1).

$$F_b = -\rho g V \tag{1}$$

Where $\rho$ is the density of water, $g$ is the gravity vector, and $V$ is the volume of water displaced by underwater snake-like robot.

**3.2.2. Analysis of Hydrodynamic Force:** Two types of hydrodynamic forces are considered in the dynamical model of the underwater snake-like robot. One is the added mass force, and the other is the drag resistance [16].

When the snake-like robot motions in water, it will cause the accelerated motion of the surrounding water which, in turn, will generate the reaction force that is greater than the inertia force because the snake-like robot and surrounding water cannot occupy the same physical space simultaneously. The difference is the added mass force $F_a$ that can be defined as Eq. (2).

$$F_a = -\rho V C_a a \tag{2}$$

Where $C_a$ is the added mass coefficient, $a$ is the angular acceleration.

The drag resistance hinders the movement of underwater snake-like robot, and the direction is opposite to the forward direction of underwater snake-like robot. In our simulation model, we assume the snake-like robot moving in still water. The drag resistance $F_d$ can be defined as Eq. (3).

$$F_d = -\frac{1}{2}\rho C_d S v \left|v\right| \quad (3)$$

Where $v$ is the relative velocity of underwater snake-like robot with respect to water, $S_v$ is the effective cross-sectional area of underwater snake-like robot, and $C_d$ is the drag coefficient that is mainly determined by the flow state, the joint module shape, and the surface roughness.

This simulation does not consider the disturbance of water, but it still can quantitatively analyze the drag resistance on the snake-like robot when moving in water.

### 3.3. Construction of Gait Model

Serpentine locomotion is a kind of motion mode of biological snakes with high efficiency and low energy consumption. The snakes walk with serpentine gaits most of the time as well as swim in water. For underwater snake-like robot, to achieve the serpentine movement is to control the yaw joints or the horizontal joints of spatial configuration swinging according to certain rules, and make the pitch joints zero position or follow-up at the same time. In the winding movement, each part of the body has a similar "S"-shaped trajectory called the serpentine curve. Here, we adopt a simplified serpentine curve [17] as the movement trajectory of underwater snake-like robot. The simplified serpentine curve is shown in Figure 4.

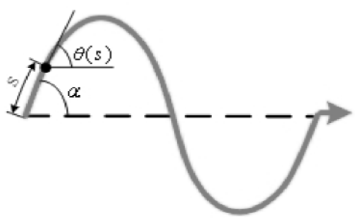


**Figure 4. The Simplified Serpentine Curve**

The curvature $\rho$ of the serpentine curve can be defined as Eq. (4).

$$\rho(\theta) = -\alpha b \sin(bs) \quad (4)$$

Where $\alpha$ is the initial corner, $b$ is a proportionality constant, $s$ is the winding angle. After the discretization of serpentine curve, a series of joint angle functions of underwater snake-like robot can be attained that are varied over time $t$, the rotation angle $\varphi$ around $x$-axis of all joints is given by the following:

$$\begin{cases} \varphi_i(t) = A\sin\left(\omega t + (i-1)\beta\right), i = 2, 3, \cdots, 9 \\ \varphi_j(t) = 0 \end{cases} \quad (5)$$

Where $t$ is time, $i$ and $j$ are the serial number of yaw joints and pitch joints, respectively, $A$ is the amplitude of the motion, $\omega$ is the frequency of joint wave, and $\beta$ is the phase offset indicating the number of wave propagation. As can be seen from (5), the motion of the yaw joints approximately obeys the sine law.

In practice, underwater snake-like robots are often equipped with cameras and sensors. In order to obtain stable favorable environment information and keep the forward direction of the body, the snakehead should always keep pointing the forward direction of movement wave in the serpentine movement. Therefore, the snakehead joint angle function $\varphi_h(t)$ can be defined as Eq. (6).

$$\varphi_h(t) = -A\cos(\omega t + (n-0.5)\beta) \tag{6}$$

Where *n* is the number of the joints. Next, based on the above simulation platform, we give the analysis of the effect of the density ratio and serpentine movement gait parameters on the motion performance of underwater snake-like robot.

## 4. Stimulation and Analysis

### 4.1. Simulation Initialization

In this paper, the parameters of the virtual prototype can be selected according to the physical prototype. The basic parameters of the physical prototype are shown in Table 1.

**Table 1. Initialization Parameters of Virtual Prototype**

| number of joint | overall length (cm) | circumference (cm) | length of joint (cm) | maximum effective swing angle (°) |
|---|---|---|---|---|
| 9 | 162 | 24 | 18 | 80 |

The initialization settings of ADAMS simulation software are as follows: simulation time is set to 50 seconds, step length is set to 0.01, and pitch joint rotation angle is set to 0 degree. The joint angle function for yaw joints can be defined as Eq. (7).

$$\begin{cases} \varphi_h = A * \cos(\omega t + (9-0.5) * \beta) \\ \varphi_i = A * \sin(\omega t + (i-1) * \beta) \qquad i = 2 \sim 8 \end{cases} \tag{7}$$

To facilitate studying the influence of the density ratio on the motion performance of underwater snake-like robot, we set a design variable $k_d$ to describe and parameterize the density ratio in ADAMS software. The variable $k_d$ is defined as Eq. (8).

$$k_d = \frac{m}{V} / \rho \tag{8}$$

Where *m* is the total mass of underwater snake-like robot, *V* is the total volume of robot, $\rho$ is the density of water, *V* and $\rho$ are constants, and *m* is a variable.

### 4.2 Stimulation of the Density Ratio

In order to study the influence of the density ratio on the motion performance of the snake-like robot, we first assign the values to the serpentine gait parameters *A*, $\omega$, and $\beta$ that can be obtained from experiments. When underwater snake-like robot moves forward at the fastest speed, the experience values of above parameters are as follows, i.e., *A*=0.64rad, $\omega$=3Hz, and $\beta$=1.05rad.

Using the above parameter values and changing the density ratio $k_d$ that varies from 0.3 to 1, the relationship between the locomotion speed and the density ratio can be diagramed in figure 5.

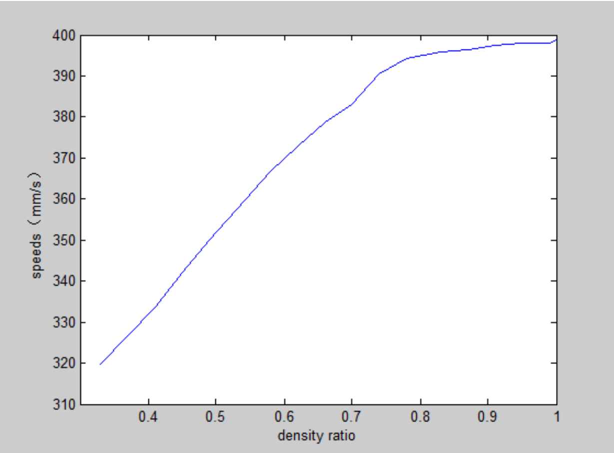


**Figure 5. Locomotion Speed with the Density Ratio**

As can be seen from the simulation results, with the increase of the density ratio, the forward speed of underwater snake-like robot is also increasing, but the growth rate is gradually reduced. When the density ratio is less than 0.75, the forward speed of the robot rapidly increases with the increase of the density ratio. When the density ratio is greater than 0.75, the growth rate of speed is more and more slow and finally tends to be stable.

The possible causes of this phenomenon is as follows: when the density ratio is small (i.e., $k_d$ < 0.75), with the increase of the density ratio the volume of snake-like robot submerged in water increases rapidly, which makes the added mass force increasing faster than the drag resistance. When the density ratio is larger (i.e., $k_d$ > 0.75), with the increase of the density ratio the volume of snake-like robot submerged in water increases slowly, which makes the added mass force increasing slower than the drag resistance. Especially, when the value of the density ratio is close to 1, the speed tends to be stable.

Take $A$=0.64rad, $\omega$=3.0Hz, and $\beta$=1.05rad, and change the density ratio that varies from 0.3 to 1, the relationship between the output power of the motor and the density ratio can be diagramed in figure 6.

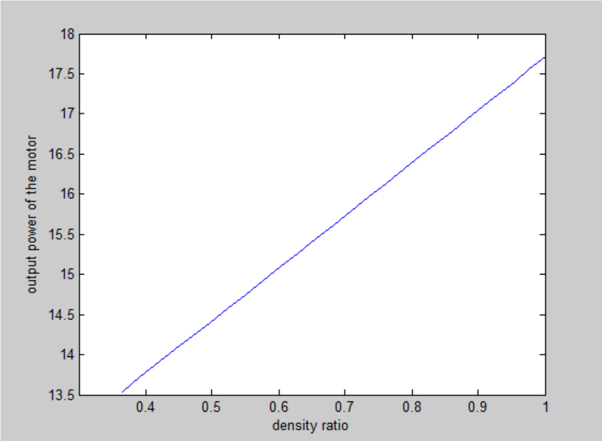


**Figure 6. Output Power of the Motor with the Density Ratio**

As can be seen from figure 6, the output power of the motor linearly increases with the density ratio. This is because the drag resistance on the underwater snake-like robot increases with the increase of the density ratio. In order to ensure the output required by winding gaits, the motor must increases the output power to overcome the drag force.

Based on the relationship between the forward speed and the density ratio together with the output power of motor and the density ratio, the relationship between the energy consumption and the density ratio can be attained under the condition of underwater snake-like robot moving forward the same distance, which is shown in figure 7.

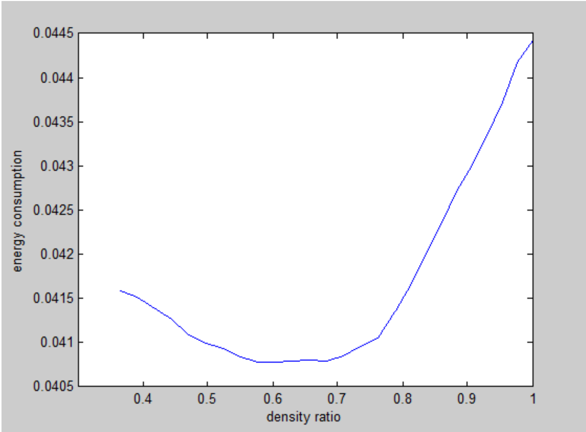


**Figure 7. Energy Consumption of the Motor with the Density Ratio**

From figure 7, we get the optimal value of the density ratio that is equal to 0.7, which makes underwater snake-like robot consumes minimum energy.

From the above simulation results about the influence of the density ratio on the locomotion speed, output power, and energy consumption, we know that the density ratio has a great influence on the motion performance of underwater snake-like robot. But, this performance improvement by simply changing the density ratio is limited. Next, we analyze the comprehensive influences on the motion performance by changing the density ratio and the serpentine gait parameters simultaneously.

### 4.3 Stimulation of Serpentine Gait Parameters

Take $k_d$ =0.7, $\omega$=3.0Hz, and $\beta$=1.05rad, and change the oscillation amplitude $A$ of the joints from 0 to 0.9rad, the relationship between the locomotion speed and the amplitude of the joints is shown in figure 8.

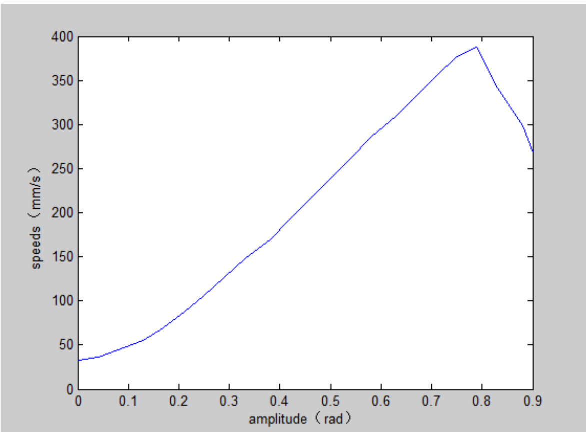


**Figure 8. Locomotion Speed with the Amplitude**

As can be seen from figure 8, when the oscillation amplitude of the joint is less than 0.8rad, the speed and the amplitude is positively correlated. When the amplitude is greater than 0.8rad, with the amplitude increasing the speed reduces instead. This is because large oscillation amplitude of the joints makes the movement of underwater snake-like robot become unstable. When the amplitude increases to a certain extent, the swing direction of the robot is opposite to the forward direction, which offsets part of the added mass force, so the forward speed reduces.

Take $k_d$ =0.7, $A$=0.64rad, and $\beta$=1.05rad, and change the oscillation frequency $\omega$ of the yaw from 0 to 10Hz, the relationship between the oscillation frequency and the locomotion speed as well as the oscillation frequency and the maximum output torque of the motor is shown in figure 9.

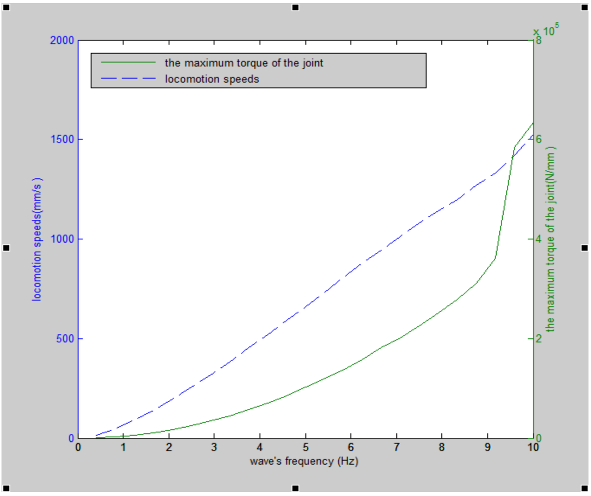


**Figure 9. Locomotion Speed and the Maximum Output Torque of the Motor with the Frequency**

The simulation results of figure 9 show that with the increase of oscillation frequency, the forward speed of the robot increases sharply as wells as the maximum output torque of the motor.

In reality, the oscillation frequency of underwater snake-like robot is restricted to the maximum torque outputted by the motor. Changing the frequency can quickly change the speed, and changing the sign of $\omega$ from positive to negative can change the motion direction of the robot, and vice versa. The frequency only affects the movement speed of the robot rather than its configurations.

Take $k_d$ =0.7, $A$=0.64rad, and $\omega$=3.0Hz, and change the value of $\beta$ from 0 to 3rad, the relationship between locomotion speed and the phase offset is shown in figure 10.

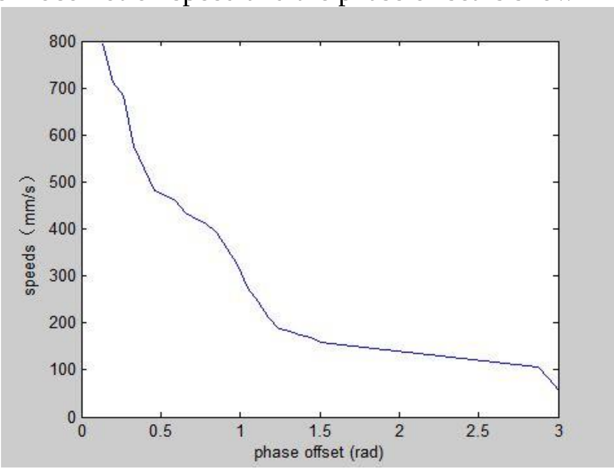


**Figure 10. Locomotion Speed with the Phase Offset**

As can be seen from the simulation results, with the increase of the phase offset, the winding motion cycle also increases accordingly and the forward speed of the robot continuously reduces.

The parameter $\beta$ determines the phase difference of adjacent joints, and also determines the number of the winding curve cycle. When the value of $\beta$ increases to a certain extent, it forms too many winding curve cycles, which is not conducive to the movement of underwater snake-like robot. When the phase offset is small (i.e., $\beta < 0.4$), the robot moves by peristalsis, and the motion trajectory is no longer a serpentine curve. When the phase offset is less than 0.2, the robot is almost in a straight line. Because the oscillation amplitude is too small to provide enough power, the robot can't move forward.

## 5. Conclusion

In this paper, a simulation platform for serpentine locomotion of underwater snake-like robot is established with the ADAMS software. After introducing the density ratio, the influence of the density ratio and gait parameters is deeply researched on the motion performance of underwater snake-like robot. By analyzing the simulation results, we get the following conclusion.

When underwater snake-like robot motions with serpentine curve, the greater the density ratio, the greater the speed, and the greater the output power of the motor. When the robot motions forward the same distance in water, the energy consumption of the robot is the lowest with the density ratio equaling 0.7.

Reasonably increasing the oscillation amplitude of joints can improve the forward speed of the snake-like robot in water. When the amplitude is more than a critical value, the speed and the stability of robot will be reduced. Within the allowable range of maximal output torque of the motor, increasing the oscillation frequency of joints can significantly increase the forward speed of the robot. But the maximal output torque of the motor is subject to the conditions of the mechanical structure of underwater snake-like robot. Fewer number of serpentine curve cycles can be able to make the joint modules fully swing to increase the forward speed.

Considering the density ratio and serpentine gait parameters simultaneously makes the virtual prototype more truly simulate the movement and the force of the physical prototype of underwater snake-like robot.

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## References

[1] P. Liljeback, K. Y. Pettersen, O. Stavdahl and J. T. Gravdahl, “Snake Robots: Modelling, Mechatronics, and Control”, **(2013)**; Springer-Verlag, Berlin.

[2] P. Liljeback, K. Y. Pettersen, O. Stavdahl and J. T. Gravdahl, “Hybrid modelling and control of obstacle-aided snake robot locomotion”, IEEE Transactions on Robotics, vol. 26, no. 5, **(2010)**, pp. 781-799.

[3] A. A. Transeth, R. I. Leine, C. Glocker, K. Y. Pettersen and P. Liljeback, “Snake robot obstacle-aided locomotion: modeling, simulation and experiments”, IEEE Transactions on Robotics, vol. 24, no. 1, **(2008)**, pp. 88-103.

[4] H. Yamada, S. Chigisaki, M. Mori, K. Takita, K. Ogami and S. Hirose, “Development of amphibious snake-like robot ACM-R5”, Proceedings of 36th International Symposium on Robotics, **(2005)**; Tokyo, Japan.

[5] A. Crespi, A. Badertscher, A. Guignard and A. Ijspeert, “Swimming and crawling with an amphibious snake robot”, Proceedings of the IEEE International Conference on Robotics and Automation, **(2005)**; Barcelona, Spain.

 

[6] F. Boyer, D. Chablat, P. Lemoine and P. Wenger, "The eel-like robot, Proceedings of ASME Design Engineering Technical Conferences", **(2009)**; San Diego, United States.
[7] S. Chen, X. Li, K. Lu, Y. Fang and W. Wang, "Gait stability and movement of snake-like robots", International Journal of Advanced Robotic Systems, vol. 9, **(2012)**.
[8] T. Matsuo, T. Sonoda and K. Ishii, "A design method of CPG network using energy efficiency to control a snake-like robot", Proceedings of 5th International Conference on Emerging Trends in Engineering and Technology, **(2012)**; Himeji, Japan.
[9] K. Yang, Y. Xu, G. Tong and C. Wu, "Kane's approach to modeling underwater snake-like robot", Proceedings of the International Conference on Information Technology and Software Engineering, Springer Berlin Heidelberg, **(2013)**, pp. 631-639.
[10] C. Ye, S. Ma, B. Li, Y. Wang and J. Tao, "Dynamics analysis on serpentine locomotion of a new snake-like robot", Robot, vol. 27, no. 6, **(2005)**.
[11] Z. Zuo, Z. Wang, B. Li and S. Ma, "Serpentine locomotion of a snake-like robot in water environment", Proceedings of the IEEE International Conference on Robotics and Biomimetics, **(2009)**; Bangkok, Thailand.
[12] M. Yamakita, N. Kamamichi, T. Kozuki, K. Asaka and Z. W. Luo, "A snake-like swimming robot using IPMC actuator and verification of doping effect", Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, **(2005)**.
[13] S. Yu, S. Ma, B. Li and Y. Wang, "Gait generation and analysis for snake-like robots, Robot, vol. 33, no. 3, **(2011)**, pp. 371-378.
[14] C. Ye, "Mechanism design and locomotion control of snake-like robots", Master Thesis of Shenyang Institute of Automation, Chinese Academy of Sciences, **(2005)**.
[15] F. White, "Fluid Mechanics, McGraw-Hill Series in Mechanical Engineering", McGraw-Hill Higher Education, **(2003)**.
[16] W. Khalil, G. Gallot, O. Ibrahim and F. Boyer, "Dynamic modeling of a 3d serial eel-like robot", Proceedings of IEEE International Conference on Robotics and Automation, **(2005)**; Barcelona, Spain.
[17] C. Li, "Study on locomotion of snake robot for adaptation to the environment on locomotion of snake robot for adaptation to the environment", Master Thesis of Shenyang Institute of Automation, Chinese Academy of Sciences, **(2004)**.

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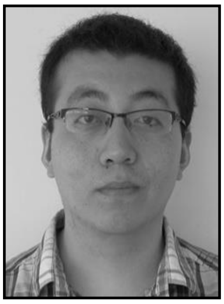

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