Design and Kinetic Analysis of a Biomimetic Underwater Vehicle with Two Undulating Long-fins

WEI Qing-Ping1 WANG Shuo1 DONG Xiang2 SHANG Liu-Ji1 TAN Min1

Abstract A biomimetic underwater vehicle propelled by two undulating long-fins is introduced in this paper. The concerned vehicle is propelled by two symmetrical undulating long-fins installed on both sides. Ten servo motors are employed to drive the long-fins and cosine wave function is employed for motor control. A real-time control system is designed for controlling the long-fins by adjusting its oscillating frequency and oscillating amplitude. An inertial measurement unit is installed to collect the accelerations and angular velocity. To obtain the relationship between oscillating frequency/amplitude and swimming performance, kinematic analysis and hydromechanic analysis are given. By dividing the long-fin into many small elements and computing the hydrodynamic force acting on each element, the instantaneous thrust generated by the long-fin is obtained. Then the average thrust of the long-fin is obtained by summing up the forces acted on the elements in one undulating period. Then swimming experiments are carried out to validate the vehicle design and kinematic analysis and hydromechanic analysis. And two swimming motion modes including marching and rotating locomotion are chosen. Finally, discussions between the swimming performance and the oscillating parameters are given.

Key words Autonomous underwater vehicle, biomimetic robot fish, kinematic modeling, robot control

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Biomimetic underwater vehicle (BUV) research is driven by the demands of applications and fitness in underwater complex circumstance. At present, more complicated operations in dangerous and worse environment make traditional autonomous underwater vehicles (AUV) inadequate both in autonomous ability and hydrodynamic efficiency. Along with increasing demands for high efficiency propulsion, robustness and long work duration, researches on AUV have made great progress, especially in biomimetic underwater vehicles.

Several bio-inspired underwater vehicles have been built. The earliest undulating fin device using the parallel bellows actuator was developed by Sfakiotakis in Heriot-Watt University[1]. Northwestern University designed a bio-inspired robotic fin which used eight servo motors to drive the long-fin[2–3]. Osaka University in Japan and Nanyang Technological University in Singapore proposed two bio-inspired vehicles[4–5]. Zhejiang University in China developed a biomimetic vehicle using a wave-like locomotion system[6]. Institute of Automation, Chinese Academy of Sciences also designed a biomimetic underwater vehicle, propelled by two symmetrical undulating long-fins, which can execute multi motion modes[7]. Based on respective architecture, kinetic analysis is often used to research the propulsion. Cochran et al. analyzed hydrodynamic force generated by fish body oscillating in water[8]. They model robotic fish based on “vortex shedding”. Willy et al. proposed a modeling method based on simplifying two adjacent fin-rays as two-degree-of-freedom mechanisms[9]. MacIver et al. proposed an idealized ellipsoidal body model based on Kirchhoff’s equations, which treated robotic fish as a rigid ellipsoid[10]. Meanwhile, some researchers use computational fluid dynamics (CFD) method to analyze the propulsion[11–13]. And according to the underwater robotic vehicle with three-layer structure, some researchers proposed corresponding modeling algorithms[14]. Earlier, kinetic analysis based on 3-D wave plate theory was proposed by Cheng et al.[15]. However, most studies are focused on exploring the mechanism of undulating long-fins and designing new underwater thrusters. There are few researches on accurate relationship between swimming performance and motion parameters. Therefore, there is a lot of works to do on BUV researches.

In this paper, our underwater vehicle has two symmetrical bilateral long-fins. And each long-fin is driven by ten servo motors. A set of inertial measurements unit is installed on its body to collect inertial information. Its control system design may be divided into three parts: embedded control unit, driving unit, and IMU (Inertial measurement unit). The IMU is used to collect velocity information of the vehicle. The embedded control system based on ARM-Linux is used to process the inertial information and send control command to the driving unit. And the driving unit is used to produce pulse width modulation (PWM) signals for the two long-fins according to the command. Based on the design, kinematic analysis and hydromechanic analysis are taken to research the relationship between oscillating frequency/amplitude and thrust. Through dividing the long-fin into many small elements and summing up the hydrodynamic force acted on each element, the thrust for each long-fin is obtained. To validate the kinematic analysis and hydromechanic analysis, two kinds of experiments, i.e., thrust experiment and motion experiment, are carried out respectively. Obviously, the analysis is very useful for the choice of motion parameters of the biomimetic underwater vehicle.

The remainder of the paper is organized as follows. Section 1 introduces the vehicle mechanism design and control system design. Kinematic analysis and hydromechanic analysis are proposed in Section 2. Section 3 presents the experiments and comparison between the experiment results and theoretical analysis. Finally, the conclusions are given in Section 4.
1 Vehicle design

Taeniura Lymma is a kind of Dasyatidae fish in the Pacific with two undulating long-fins, which employs median and/or paired fin (MPF) propulsion. By contrast with body and/or caudal fin (BCF) propulsion, MPF propulsion exhibits high maneuverability and dexterous manipulation. Motivated by the idea, our underwater vehicle prototype is designed.

1.1 Mechanism design

The biomimetic underwater vehicle consists of vehicle body and two long-fins, as shown in Fig. 1. The rigid body of the vehicle is made of glass fiber reinforced plastic and ten servo-motors are installed on each side which is used to drive the long-fin.

Each long-fin shown in Fig. 2 is a skeleton covered by soft, elastic membrane. Ten fin-rays connected with the servo-motors are distributed symmetrically in the membrane. Table 1 shows the structure parameters of the vehicle. All the fin-rays are fixed on the vehicle body. Servo-motors oscillate the ten fin-rays and make the membrane bend at some waveform when the biomimetic underwater vehicle swims in water. Each fin-ray can be controlled by the corresponding servo independently. Therefore, different control strategies can be taken to make the fin-ray oscillating to generate thrust and torsional moment.

1.2 Control system design

Control system design for the vehicle contains three primary parts: embedded control unit, driving unit and IMU. PC control center is designed for remote control, which use a wireless module to communicate with the embedded control center. All the control system carries out the following missions: receiving and sending command information, collecting and processing sensor data, and executing control algorithms etc, as shown by Fig. 3.

![Fig. 1 Vehicle prototype](image1)

![Fig. 2 Long-fin](image2)

**Table 1 Structure parameters of underwater vehicle**

<table>
<thead>
<tr>
<th>Name of structure division</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of vehicle</td>
<td>817 mm</td>
</tr>
<tr>
<td>Width of vehicle</td>
<td>401 mm</td>
</tr>
<tr>
<td>Height of vehicle</td>
<td>158 mm</td>
</tr>
<tr>
<td>Length of vehicle</td>
<td>460 mm</td>
</tr>
<tr>
<td>Width of membrane</td>
<td>97.4 mm</td>
</tr>
<tr>
<td>Thickness of membrane</td>
<td>1 mm</td>
</tr>
<tr>
<td>Number of ray-fin</td>
<td>10</td>
</tr>
<tr>
<td>Length of ray-fin</td>
<td>97.4 mm</td>
</tr>
<tr>
<td>Oscillating frequency</td>
<td>0 ~ 3 Hz</td>
</tr>
<tr>
<td>Oscillating amplitude</td>
<td>0 ~ π/2</td>
</tr>
<tr>
<td>Phase difference</td>
<td>π/5</td>
</tr>
<tr>
<td>Interval between ray-fins</td>
<td>51.1 mm</td>
</tr>
</tbody>
</table>

External wireless module unit in Fig. 3 is designed for wireless command reception in remote manual control. And the IMU is integrated in the vehicle system. Both the units are based on interrupt mechanism, which ensures the quick-response character of the vehicle. The control system, which embeds a modified embedded real-time Linux OS, receives and processes the data from the two units mentioned above and then analyzes the control command, namely the frequency/amplitude of the two long-fins. Next, the control commands are sent to the driving unit. In addition, multi-thread synchronization method is used in the control system to ensure real-time control.

The driving unit employs FPGA (Field programmable gate array) to drive the servo motors of the two long-fins. According to the control demands, it is necessary to achieve independent control for each long-fin. There are mostly four missions for the driving system: receiving and parsing the commands from embedded control unit, generating PWM signals, switching motion mode, and on-line signal control for each long-fin.

2 Kinematic analysis and hydromechanic analysis

Water is an impressible fluid, so any movements of long-fin will make the vehicle body in motion[16]. Therefore coordination control of the two long-fins can generate varied locomotion. Obviously, the oscillating amplitude and frequency of the fin-rays are the keys how the biomimetic underwater vehicle works.

2.1 Kinematic analysis

According to [17], the oscillating discipline is employed for each fin-ray:

\[
\theta(s, t) = (c_0 + c_1 s + c_2 s^2) \cos(2\pi ft + ks + \phi_0) = \theta_m \cos(2\pi f t + ks + \phi_0)
\]
respectively, for example, as shown in Fig. 4. According to (2),
the instantaneous angles of fin-ray 1 and 2 are:

\[
\theta(S_1, t) = \theta_m \cos\left(2\pi ft - \frac{2\pi}{\lambda} S_1 + \phi_0\right) \tag{3}
\]

\[
\theta(S_2, t) = \theta_m \cos\left(2\pi ft - \frac{2\pi}{\lambda} S_2 + \phi_0\right) \tag{4}
\]

Then the angle between fin-ray 1 and 2 at time t is:

\[
\Delta\theta(S_1, 2, t) = ||\theta(S_1, t) - \theta(S_2, t)|| = \\
2\theta_m \sin\left(\frac{\pi}{\lambda}(S_2 - S_1)\right) \left|\sin\left(2\pi ft - \frac{\pi(S_1 + S_2)}{\lambda} + \phi_0\right)\right| \tag{5}
\]

Therefore, when the underwater vehicle swims, the oscillating amplitude must obey the following equation:

\[
\max(\Delta\theta(S_1, 2, t)) \leq \theta_{\text{mem}} \tag{6}
\]

In one oscillating cycle, the absolute value item can always have the maximum value of 1 at a some appropriate time. Considering that \((S_2 - S_1)\) is a constant value due to the mechanical design and that \(\lambda\) is kept as one fixed value, the oscillating amplitude \(\theta_m\) should satisfy the following relationship:

\[
\theta_m \leq \theta_{\text{mem}} / 2 \sin\left(\frac{\pi}{\lambda}(S_2 - S_1)\right) \tag{7}
\]

In the control system, the position command is sent to the servo motors periodically. After receiving the position command, the servo motors should go the specified position as quickly as they can before next command arrives. Generally, the control period is a constant. But the servo motors can only rotate some finite angles, denoted as \(\omega_{\text{servo}}\), in one control period since the maximum moving speed is finite. We assume that \(\theta_m\) and \(\lambda\) are fixed and that the time of two adjacent control command arriving are \(t_1\) and \(t_2\), respectively. According to (2), the instantaneous angles of one fin-ray, \(s\), at time \(t_1\) and \(t_2\) are:

\[
\theta(s, t_1) = \theta_m \cos\left(2\pi f t_1 - \frac{2\pi}{\lambda} + \phi_0\right) \tag{8}
\]

\[
\theta(s, t_2) = \theta_m \cos\left(2\pi f t_2 - \frac{2\pi}{\lambda} + \phi_0\right) \tag{9}
\]

Therefore, the angle that the servo motors should rotate in one period is:

\[
\Delta\theta_T(s, t) = ||\theta(s, t_1) - \theta(s, t_2)|| = \\
2\theta_m \left|\sin\left(\pi f (t_1 + t_2) - \frac{2\pi}{\lambda} s + \phi_0\right)\sin(\pi f T)\right| \tag{10}
\]

where \(T\) is the control period. Since the control period is much smaller than the oscillating period, the angle, \(\pi f T\), satisfies the relationship: \(0 < \pi f T < \pi/2\). Then (10) can be simplified to:

\[
\Delta\theta_T(s, t) = \\
2\theta_m \sin(\pi f T) \left|\sin\left(\pi f (t_1 + t_2) - \frac{2\pi}{\lambda} s + \phi_0\right)\right| \tag{11}
\]

According the discussion above, when the underwater vehicle swims, the oscillating frequency \(f\) should obey the following relationship:

\[
\max(\Delta\theta_T(s, t)) \leq \omega_{\text{servo}} \tag{12}
\]

No matter what the oscillating frequency is, the absolute value item in (11) can reach the maximum value of 1 at some appropriate time of \(t_1\) and \(t_2\). Therefore, according to (11) and (12), the oscillating frequency should obey the following relationship:

\[
f \leq \frac{1}{T} \arcsin\left(\frac{\omega_{\text{servo}}}{2\theta_m}\right) \tag{13}
\]

Different oscillating discipline between the two long-fins may generate many kinds of locomotion modes. But according to the discussion above, it is motion parameter, namely fin-ray’s oscillating amplitude and oscillating frequency, should not violate the constraints defined by (7) and (13) when the biomimetic underwater vehicle swims.
2.2 Hydromechanic analysis

Swimming performance of the vehicle is decided by the thrust generated by the long-fin. And the thrust of the long-fin is produced by the interaction of the membrane and the fluid. The surface of the membrane is changed cyclically, so we choose one period of the long-fin motion to calculate the average thrust. Obviously, the whole membrane may be divided into many small elements, and the forces acted on the elements in the period are calculated and summed to obtain the average thrust.

The following dynamic analysis for the long-fin is based on three assumptions: 1) the undulating motions of the fin rays make the long-fin move forward straightly along axis \( O_x \); 2) the undulating motions are with respect to axis \( O_x \); 3) the wave number on the long-fin is integer.

As shown in Fig. 3, the long-fin consists of supporter, servo motor, fin ray, and membrane. Different fin rays are driven by different servo motors which are installed in the supporter. And all the fin rays are connected and covered by the membrane. The servo motors rotate according to special control strategies to drive the fin rays, and the fin rays make the membrane undulating in the water to generate thrust. For the purpose of dynamic analysis, the coordinates \( O_x, Y, Z \) for the whole long-fin and the coordinates \( O_x, Y, Z \) for each fin ray are set up. Assumed that the fin ray motion is cyclic motion in the plane \( Y, O_x, Z_r \) and expressed as below.

\[
\theta(t) = \theta_m f(t) \quad (14)
\]

where \( \theta_m \) is the maximal oscillating amplitude of the servo motor, \( f(t) \) is the cyclic motion function. And the motion of a point on the fin ray can be described as follow with respect to the coordinates \( O_x, Y, Z_r \).

\[
x_r(h, t) = 0 \\
y_r(h, t) = h \cos[\theta(t)] \\
z_r(h, t) = h \sin[\theta(t)]
\]

(15)

where \( h \) is the distance between a point on the fin ray and the origin of its fin-ray coordinates, \( h \in [0, H] \), and \( H \) is the length of the fin ray, \( t \) is time.

In the coordinates \( O_x, Y, Z_r \), each fin ray has same cyclic motion expression but has its own phase related to its position on axis \( O_x \). And the motion of one point on the membrane is described as below with respect to the coordinates \( O_x, X_q, Y_q, Z_q \).

\[
x_q(s, h, t) = s \\
y_q(s, h, t) = h \cos[\theta(s, t)] \\
z_q(s, h, t) = h \sin[\theta(s, t)]
\]

(16)

where \( s \) is the point position on axis \( O_x \), \( s \in [0, S] \). \( S \) is the length of the membrane.

As known, the interaction between the small element surface and fluid may be described according to the following equations:

\[
\begin{align*}
F_n &= \frac{dF_n}{dS} = -\frac{1}{2} \rho C_n \| V_n \| V_n \\
F_r &= \frac{dF_r}{dS} = -\frac{1}{2} \rho C_r \| V_r \| V_r
\end{align*}
\]

(17)

where \( dF_n \) is the normal transient force acted on the element surface, \( dF_r \) is the tangential transient force acted on the element surface, \( dS \) is the area of the element, \( \rho \) is the fluid density, \( C_n \) is the coefficient of the tangential drag, \( C_r \) is the viscous drag coefficient, \( V_n \) is the transient normal velocity with respect to the fluid, \( V_r \) is the tangential transient velocity with respect to the fluid.

Hence the normal and tangential transient force of the long-fin can be obtained by the membrane surface integral of the forces of all the elements.

\[
\begin{align*}
F_n &= \iint_{\Omega(t)} f_n dS \\
F_r &= \iint_{\Omega(t)} f_r dS
\end{align*}
\]

(18)

where \( F_n \) is the normal transient force of the long-fin, \( F_r \) is the tangential transient force, \( \Omega(t) \) is the membrane surface at time \( t \). Because the Reynolds number of the biomimetic robot is more than \( 10^4 \), the fluid is assumed to be non-viscid fluid and the viscid effect is neglected, nearly the tangential force is neglected in the paper.

Assumed that the speed and angular velocity of the origin of the coordinates \( O_x, X_q, Y_q, Z_q \) with respect to the inertial frame are \( \dot{V}_q = (U_x, U_y, U_z)^T \) and \( \omega_q = (\omega_x, \omega_y, \omega_z)^T \) respectively, the velocity of \( P \) with respect to the inertial frame is given below.

\[
V_{ep}(s, h, t) = \frac{\partial P_q(s, h, t)}{\partial t} = \begin{bmatrix}
0 \\
-h \theta'_t \sin(\theta) \\
h \theta'_t \cos(\theta)
\end{bmatrix}
\]

(19)

where \( \theta'_t = \frac{\partial \theta(s, t)}{\partial t} = -2\pi f \theta_m \sin \left(2\pi ft - \frac{2\pi s}{\lambda} + \phi_0\right) \).

If the speed and angular velocity of the origin of the coordinates \( O_x, X_q, Y_q, Z_q \) with respect to the inertial frame are \( \dot{V}_q = (U_x, U_y, U_z)^T \) and \( \omega_q = (\omega_x, \omega_y, \omega_z)^T \) respectively, the velocity of \( P \) with respect to the inertial frame is given below.

\[
V_{ep} = V_{eq} + \omega_{eq} \times r_{eq} + V_{qp}
\]

(20)

where \( r_{eq} \) represents the position vector of \( P \) with respect to the coordinates \( O_x, X_q, Y_q, Z_q \).

The speed and angular velocity of the origin of the coordinates \( O_x, X_q, Y_q, Z_q \) with respect to the inertial frame can be assumed to be \( V_{eq} = (U_x, 0, 0)^T \) and \( \omega_{eq} = (0, 0, 0)^T \), according to the assumptions without loss of generality. Then the velocity of \( P \) with respect to the inertial frame can be expressed below.

\[
V_{ep} = V_{eq} + V_{qp} = \begin{bmatrix}
U_x \\
-h \theta'_t \sin(\theta) \\
h \theta'_t \cos(\theta)
\end{bmatrix}
\]

(21)

The normal vector of \( P \) is given in (22).

\[
n = \frac{\partial P_q(s, h, t)}{\partial s} \times \frac{\partial P_q(s, h, t)}{\partial h} = \begin{bmatrix}
-h \theta'_s \\
-sin(\theta) \\
\cos(\theta)
\end{bmatrix}
\]

(22)

where \( \theta'_s = \frac{\partial \theta(s, t)}{\partial s} = \frac{2\pi f \theta_m \sin \left(2\pi ft - \frac{2\pi s}{\lambda} + \phi_0\right)}{\lambda} \).

The normal unit vector of \( P \) is deduced from (11).

\[
n_0 = \frac{n}{\| n \|} = \frac{1}{\sqrt{(h \theta'_s)^2 + 1}} \begin{bmatrix}
-h \theta'_s \\
-sin(\theta) \\
\cos(\theta)
\end{bmatrix}
\]

(23)
And the normal transient velocity $V_{pn}$ of $P$ is

$$V_{pn} = (V_{ep} \times n_0)n_0 = -U_s \dot{h}_s' + \frac{\dot{h}_s'}{\dot{h}_s'^2 + 1}(-h\dot{\theta}_s', -\sin(\theta), \cos(\theta))^T$$ (24)

Using (17), (18) and (24), the force acted on the long-fin can be obtained with the fact that $\dot{\theta}_s = -\lambda_0 f\theta_s$.

$$F_n = -\frac{1}{2} \rho C_n \int_D \|V_{pn}\| |V_{pn}| dS = \frac{1}{2} \rho C_n \int_D \|V_{pn}\| \|n\| dS d\theta = \frac{1}{2} \rho C_n \int_D \frac{|\dot{h}_s'|}{\dot{h}_s'^2 + 1} (-h\dot{\theta}_s', -\sin(\theta), \cos(\theta))^T dS d\theta$$ (25)

So the components of the force along axis $X$, $Y$, $Z$ are expressed as follow.

$$\begin{aligned}
F_{nx} &= \frac{1}{2} \rho C_n (U_X + \lambda f)^2 \int_D \frac{|\dot{h}_s'|}{\dot{h}_s'^2 + 1} |\dot{h}_s'| dS d\theta \\
F_{nx} &= \frac{1}{2} \rho C_n (U_X + \lambda f)^2 \int_D \frac{|\dot{h}_s'|}{\dot{h}_s'^2 + 1} |\dot{h}_s'| \sin(\theta) dS d\theta \\
F_{nz} &= -\frac{1}{2} \rho C_n (U_X + \lambda f)^2 \int_D \frac{|\dot{h}_s'|}{\dot{h}_s'^2 + 1} |\dot{h}_s'| \cos(\theta) dS d\theta
\end{aligned}$$ (26)

According to the assumptions and the characteristics of trigonometric functions, the analytical expressions can be obtained as follow.

$$\begin{aligned}
F_{nx} &= \frac{1}{2} \rho C_n (U_X + \lambda f)^2 \left[ 2\pi \theta_m H^2 + \frac{n\lambda^2}{2\pi \theta_m^2} \ln^2 \lambda - \frac{n\lambda^2}{4\pi \theta_m^2} \ln^2 (\sqrt{4\pi \theta_m^2 H^2 + \lambda^2} - 2\pi \theta_m H) - \frac{n\lambda^2}{4\pi \theta_m^2} \ln^2 (\sqrt{4\pi \theta_m^2 H^2 + \lambda^2} + 2\pi \theta_m H) \right] \\
F_{ny} &= 0 \\
F_{nz} &= 0
\end{aligned}$$ (27)

When the biomimetic vehicle with long-fins moves forward straightly, the long-fins would generate thrust along the moving orientation. And the generated thrust is related to oscillating frequency, oscillating amplitude, wave length, and wave number of the long-fin.

3 Experiments and discussions

3.1 Experiments

In a swimming pool, two kinds of experiments, i.e., thrust experiments and motion experiments, were conducted with the single long-fin shown in Fig. 2 and the underwater vehicle prototype shown in Fig. 1 respectively.

3.1.1 Thrust experiments

In the thrust experiment, the single long-fin was fixed on a suspension which can slide along the rail through rolling bearings. A embedded control unit fixed on the top of suspension was used to make the single long-fin oscillates in varieties of oscillating amplitude and frequency. Power source was also fixed on the top of suspension. A push pull gage (CT BRAND CNK-50N, Wah Luen electronic tools co., ltd.) which was fixed on the pool edge was used to measure the instantaneous maximum force generated by the single long-fin. The push pull gage was linked to the suspension by use of a soft rope. Fig.5 shows the thrust experiment platform.

We examined several combinations of oscillating frequency and amplitude on single long-fin. For each value of the oscillating amplitude, the oscillating frequency was changed from 1 Hz to 3 Hz. The specific wavelength was kept at $\lambda = 1$ through all experiments.

3.1.2 Motion experiments

In the motion experiment, a PC control center sent vari-eties of control command through wireless communication module to adjust the oscillating amplitude and frequency of the vehicle. The main purposes are: 1) observing the swimming performance including maneuverability and stability; 2) measuring the vehicle’s basic motion parameters including average speed and angular velocity with different oscillating frequency and amplitude; 3) validating the kinematic analysis and dydromechanic analysis through the experiments’ results. The speed measurement for each configuration was conducted at least three times. The motion experiment was divided into two parts: experiment of marching locomotion and experiment of rotating locomotion.

During the marching experiments, several problems were considered. One is that the membrane covered on ray-fins limits ray-fin’s oscillating. The greater the oscillating amplitude is, the more obvious the limitation effect is. The other one is that there is a maximum value of hydrodynamic forces with undulating long-fins at certain amplitude. Fig. 6 shows the screenshots of marching locomotion.

Finally, the rotating locomotion experiments were performed. When the two long-fins run in opposite traveling wave direction, the hydrodynamic forces generated by both long-fins drive the vehicle into rotating locomotion. Its main function is to adjust the swimming direction of the biomimetic underwater vehicle. Fig. 7 shows the screenshots of rotating locomotion.
3.2 Results

3.2.1 Results of thrust experiments

In the thrust experiment, we have done frequency tests at 1, 1.5, 1.8, 2, 2.2, 2.5, 2.8 and 3 Hz while the oscillating amplitude changed from 15° to 40° with the step of 5°. The specific wavelength was kept at $\lambda = 1$ through all experiments. The force generated by single long-fin increases as the oscillating frequency increases when the frequency is smaller than 2.2 Hz. But when the oscillating frequency is over 2.2 Hz, the force instead decreases as the frequency increases. The similar characters can be observed when the oscillating amplitude changed from 15° to 40° and the oscillating frequency remained unchanged. The largest force, i.e., 9.8 N, generated by single long-fin can be achieved when the oscillating amplitude and oscillating frequency are 35° and 2.2 Hz respectively. Table 2 shows the instantaneous maximum force generated by single long-fin with different oscillating frequency and amplitude.

3.2.2 Results of motion experiments

We have done frequency tests at 1, 1.5, 2, 2.2 and 2.5 Hz in marching experiments. When the frequency is 1 or 1.5 Hz, the vehicle may get small speed; when the frequency is over 2.5 Hz, the produced bigger water wave makes the vehicle un-steady. Maximum speed can be achieved at 2.2 Hz. The average speed is about 232 mm/s and the maximum speed is about 370 mm/s. The average speed increases with increasing oscillating frequency in the range of [1, 2.2] Hz. When the frequency is over 2.2 Hz, the average speed declines. Fig. 8 shows the average speed at different oscillating frequency when the amplitude equals $\pi/6$.

The rotation experiments were carried out when the oscillating frequency is 1, 1.5, 2, 2.2, 2.5Hz and the amplitude also equals $\pi/6$. The maximum average angular velocity which is about 2.0 rad/s can be achieved when the oscillating frequency is about 2.2 Hz. And the vehicle’s angular velocity increases with the increasing oscillating frequency in the range of [1, 2.2] Hz. But the angular velocity declines when the oscillating frequency is over 2.2 Hz. Fig. 9 shows the experiments results of rotating locomotion.

3.3 Discussion

The goal is to design a biomimetic underwater vehicle and do the kinematic analysis and hydromechanic analysis for the vehicle. The results were satisfactory at first glance through the experiments. The vehicle shows good maneuverability under the control of real-time control system. Different oscillating frequency or amplitude brought different swimming performance. But a more in-depth study, especially the relationship between swimming performance and control parameters, shows specific complexity.

3.3.1 Stability

As an important performance for the underwater vehicle impelling in water, we have taken the stability of our vehicle into account when we design the mechanical structure. First of all, the overall structure is as far as possible symmetrical. This can reduce the pitch motion and roll motion when the vehicle is in steady state. Secondly, for our vehicle, the center of gravity is below the center of buoyancy.

### Table 2 Instantaneous maximum force (N) generated by single long-fin

<table>
<thead>
<tr>
<th>$\theta_m$ (°)</th>
<th>$f = 1.0$ Hz</th>
<th>$f = 1.5$ Hz</th>
<th>$f = 1.8$ Hz</th>
<th>$f = 2.0$ Hz</th>
<th>$f = 2.2$ Hz</th>
<th>$f = 2.5$ Hz</th>
<th>$f = 2.8$ Hz</th>
<th>$f = 3.0$ Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>15°</td>
<td>0.4</td>
<td>1.2</td>
<td>2.4</td>
<td>2.6</td>
<td>2.8</td>
<td>2.5</td>
<td>2.2</td>
<td>2.0</td>
</tr>
<tr>
<td>20°</td>
<td>1.0</td>
<td>2.4</td>
<td>3.4</td>
<td>4.0</td>
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This ensures the stability in vertical direction. And the results of experiments proved that our design is effective. While these design considerations have been taken to ensure the static stability, the dynamic stability is also important for the underwater vehicle. Due to the design for the mechanical structure, the underwater vehicle can also achieve satisfactory dynamic stability. For example, if the vehicle swims forward without rolling motion and pitching motion, the forces acting on the vehicle as shown in Fig. 10 should be balanced mutually. Namely, the buoyancy \( F_B \) equals to the gravity \( G \) and the thrust \( F_T \) equals to the resistance \( F_R \). This is a steady state. Now, if some disturbance make the vehicle produce a small pitch angle, denoted as \( \theta_p \), the forces acting on the vehicle are shown in Fig. 11. In this condition, the torque produced by gravity and buoyancy will automatically decrease the pitch angle and make the vehicle back to the steady state since the gravity and buoyancy are far greater than the thrust. In other words, the underwater vehicle has the dynamic stability. And this is consistent to rolling motion and rotation. Therefore, the underwater vehicle is stable in static or dynamic state.

![Fig. 10 Forces acting on the vehicle without pitch or roll angle](image)

![Fig. 11 Forces acting on the vehicle with pitch angle](image)

### 3.3.2 Kinematic constraints

Through the kinematic analysis mentioned in Subsection 2.1, we have known that if we want to make the vehicle oscillating at the specified amplitude, the oscillating amplitude and frequency should obey two constraints, i.e., (7) and (13), otherwise the actual oscillating amplitude will be smaller than the specified amplitude.

The interval between fin rays is a definite value once the vehicle design is done. Therefore the elasticity of membrane plays a dominate role on the amplitude constraint according to relationship (7). But when we design the vehicle, we have left enough margin to reduce the impact of amplitude constraint. So the amplitude constraint (7) is not the main issue and we will focus on the frequency constraint given by (13).

For the frequency constraint (13), it is determined by control period, characters of servo motors and the maximum specified amplitude. For our vehicle, the control period is 20 ms, i.e., \( T = 20 \) ms, and the servo motors’ maximum speed is \( 60^\circ/0.19 \) s, namely the servo motor can turn up to 6.316\(^\circ\), i.e., \( \omega_{\text{ servo}} = 6.316^\circ \). Using the above two parameters and assuming the maximum amplitude is \( \pi/6 \), the oscillating frequency \( f \) should obey the following relationship according to (13):

\[
f \leq 1.678 \text{ Hz}
\]

If the oscillating frequency is larger than 1.678 Hz, some servo motors may not reach their specified positions in one control period. Therefore the actual oscillating amplitude will be smaller than the originally specified amplitude. And the larger the frequency is, the smaller the actual amplitude is.

### 3.3.3 Thrust

In the hydromechanic analysis, i.e., (27), thrust generated by the long-fin is determined by the oscillating frequency, amplitude, wave length and length of fin ray. For the first version of our vehicle, we have tried the best to simplify the mechanical design. So we used the fin rays with the same and fixed length in our vehicle prototype. The mechanical design, servo motor’s characteristic, oscillating frequency and amplitude are concerned on researches of swimming performance, while the wave length and length of fin ray are not included. Fig. 12 shows the relationship between oscillating frequency and thrust through hydromechanics analysis mentioned in Subsection 2.2 while the oscillating amplitude equals \( \pi/6 \) and other parameters are determined by the mechanical parameters. And Fig. 13 shows the relationship between oscillating amplitude and thrust through hydromechanic analysis when the oscillating frequency equals 2 Hz and other parameters are determined by the mechanical parameters.
In Figs. 12 and 13, the hydromechanic analysis shows that the thrust always monotonically increases as the oscillating frequency or amplitude increases. But in Table 2, the thrust experiments show that the force generated by a single long-fin do not always increases along with the increasing frequency or amplitude and there exists a maximum value of the force. This can be demonstrated through the kinematic analysis mentioned in Subsection 2.1. Taking the analysis between thrust and oscillating frequency for example, the oscillating frequency cannot increase infinitely because of the limitation of servo motors and membrane covered on the fin-rays.

Here in order to facilitate the discussion, we assume that the oscillating frequency increases from 0 Hz to 3 Hz. In the beginning, the oscillating frequency is small enough to satisfy the relationship given by (13), namely the frequency is smaller than 1.678 Hz according to (28). Therefore the vehicle oscillates at the specified amplitude and the thrust increases along with the increasing frequency according to (27). The results of thrust experiments shown in Table 2 also show the same trend between thrust and oscillating frequency.

If the oscillating frequency is larger than 1.678 Hz, the relationship (13) is violated. From the discussion of kinematic constraints mentioned in Subsection 3.2.2, we know that the actual oscillating amplitude will decrease as the frequency increases. From Fig. 13, we can know that the thrust will decrease as the amplitude decreases. But since the amount of thrust decrease caused by the decrease of amplitude is smaller than the amount of thrust increase caused by the increase of frequency, the thrust will continue to increase along with the increasing frequency. This is consistent with the results of thrust experiments shown in Table 2 because the force generated by single long-fin still increase along with the increasing frequency when the frequency is larger than 1.678 Hz.

As the frequency continues to increase, the oscillating amplitude will be smaller and smaller. Then the amount of thrust decrease caused by the decrease of amplitude will be larger and larger. So there is a moment that the amount of thrust decrease caused by the decrease of amplitude is large enough to cancel out the amount of thrust increase caused by the increase of frequency. In this moment, the maximum thrust can be achieved. Hereafter, the thrust will decreases along with the increasing frequency. This changing trend can also be found in the results of thrust experiments shown in Table 2. The maximum force can be achieved when the frequency is 2.2 Hz and the force will decrease along with the increasing frequency when the frequency is larger than 2.2 Hz.

Based on the theoretical analysis of thrust given by (27) and the results of thrust experiment shown in Table 2, the relationship between thrust and oscillating amplitude may also shows the same characters.

Moreover, compared to the results of thrust experiment, the theoretical thrust calculated by (27) is smaller at the same oscillating frequency and amplitude. This may be caused by the following two factors. 1) In the thrust experiment, the results show the instantaneous maximum force acted on the push pull gage. But the thrust calculated by (27) is an average force of one control period. So the calculated thrust should be smaller than the force recorded in thrust experiment. 2) In the thrust experiment platform, the suspension is linked to the push pull gage with a soft rope and the push pull gage records the instantaneous maximum force which acted on it. During the thrust experiment, the suspension will be accelerated for a little while before the rope reaches its limit length. When the rope reaches its limit length, the momentum of suspension will transform to a force exerted on the suspension according to the impulse theorem. So the force acted on the push pull gage consists of two force, namely the thrust generated by single long-fin and the force transformed from the momentum of suspension. Therefore the push pull gage will record the maximum thrust and the results of thrust experiment shown in Table 2. But on the other hand, the fluid resistance has a quadratic dependence with the swimming speed and we did not take full account of drag reduction. Therefore the swimming speed of our vehicle is not high. The vehicle swims fastest when the oscillating frequency is 2.2 Hz at which the thrust is largest at one specified amplitude.

4 Conclusions

In this paper, a biomimetic underwater vehicle with two undulating long-fins is introduced. Its real-time control may be achieved by adjusting the oscillating frequency and amplitude. An inertial unit is designed for pose information collection. To explore the relationship between oscillating frequency/amplitude and swimming performance, kinematic analysis and hydromechanic analysis are conducted. Experiments showed the good swimming performance of the biomimetic underwater vehicle and discussion gives relevant analysis about the swimming performance and vehicle design. In nature, the fin-rays of Taeniura are not in the same length. But what is the role of the fin-rays with different length in enhancing Taeniura’s maneuverability and efficiency? We will focus on this issue in our future research.

References


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