Hydrodynamic Performance Analysis of a Biomimetic Manta Ray Underwater Glider
Zhenyu Wang, Jiancheng Yu, Aiqun Zhang

Abstract—A biomimetic manta ray underwater glider actuated by buoyance is presented. Firstly, the hydrodynamic structure shape of the biomimetic manta ray underwater glider is established with reference to the appearance of manta rays. Secondly, the steady motion of the biomimetic manta ray underwater glider in the vertical plane is analyzed and a simple kinematic model of the biomimetic manta ray underwater glider is built. Thirdly, the hydrodynamic performance of the biomimetic manta ray underwater glider is analyzed through commercial software CFX, and the variation of lift and drag along with the changing of the net buoyancy and center of gravity position is estimated. Finally, compared with classical shape designs in lift-drag ratio and gliding speed, the biomimetic manta ray underwater glider have better hydraulic performances with large angle of attack and small attitude angle.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>geodetic coordinate system</td>
</tr>
<tr>
<td>G</td>
<td>carrier coordinate system</td>
</tr>
<tr>
<td>( \theta )</td>
<td>pitch angle</td>
</tr>
<tr>
<td>( \psi )</td>
<td>yaw angle</td>
</tr>
<tr>
<td>( \phi )</td>
<td>roll angle</td>
</tr>
<tr>
<td>( V_1, V_3 )</td>
<td>velocity</td>
</tr>
<tr>
<td>( \omega )</td>
<td>angular velocity</td>
</tr>
<tr>
<td>( m_b )</td>
<td>net buoyancy mass</td>
</tr>
<tr>
<td>( X_G )</td>
<td>displacement of the center of gravity</td>
</tr>
<tr>
<td>( u_0 )</td>
<td>momentum change rate of ballast load</td>
</tr>
<tr>
<td>( u_1 )</td>
<td>momentum change rate of sliding mass</td>
</tr>
<tr>
<td>( m_p )</td>
<td>quality of pumping and drainage water</td>
</tr>
<tr>
<td>( M_{DL} )</td>
<td>pitching moment of additional mass</td>
</tr>
<tr>
<td>L</td>
<td>lift</td>
</tr>
<tr>
<td>D</td>
<td>drag</td>
</tr>
<tr>
<td>M</td>
<td>moment</td>
</tr>
<tr>
<td>( K_{DD}, K_D )</td>
<td>quantized coefficient of drag</td>
</tr>
<tr>
<td>( K_{LL}, K_L )</td>
<td>quantized coefficient of lift</td>
</tr>
<tr>
<td>( K_{MM}, K_M )</td>
<td>quantized coefficient of moment</td>
</tr>
</tbody>
</table>

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I. INTRODUCTION

The autonomous underwater glider (AUG), as a specific autonomous underwater vehicle. Rise or sink through the ocean by modulates its buoyancy, shift the center of mass relative to the center of buoyancy to control pitch and roll attitude. The endurance is calculated by monthly and annual [1][2][3]. This concept of underwater glider was initially conceived by Henry Stommel [4]. Since 1995, US get funded under the Office of Naval Research (ONR), it developed SLOCUM, Seaglider, Spray and other underwater glider which can work independently for a long time [5-7].

Recent years, with the progress of bionics, robotics, mechanics, new materials science, automatic control theory and other disciplines, as well as the increased development of marine economy and military demands, researchers set their sights on the movement mechanism of organisms which living in the water. This organisms have the advantages of high efficiency, low noise, high speed, high mobility and so on. Estonia scholar Anton, who developed the imitation pectoral fluctuation mechanism metal composite ion exchange membrane driven [10]. Epstein developed the bionic ribbon albacore pusher [11]. Yamamoto imitation double mouth kiss manta ray robot fish based on the principle of flapping wing [12]. China National University of Defense Technology study the long flexible fin propulsion fluctuations bionic underwater vehicle propulsion mode and pectoral fins swing robot fish [13], [14].

After millions of years of evolution, manta rays’ pectoral fins and body mix together perfectly, this shape reduces the resistance effectively, while improving the gliding speed and the ability of flow resistance. This shape can be will adapted to the special environment of the ocean. Biomimetic manta ray underwater glider can effectively improve the efficiency of the hydrodynamic, make the hydrodynamic loads achieve the best distribution, while increasing the effective load space. This paper research the hydrodynamic characteristics of biomimetic manta ray underwater glider, the hydrodynamic structure shape of the biomimetic manta ray underwater glider is established with reference to the appearance of manta rays. The steady motion of the biomimetic manta ray underwater glider in the vertical plane is analyzed and a simple kinematic model of the biomimetic manta ray underwater glider is built. The variation of lift and drag alone with the changing of the net buoyancy and center of gravity position is estimated. Compared with classical shape designs in
lift-drag ratio and gliding speed, the biomimetic manta ray underwater glider have better hydraulic performances with large angle of attack and small attitude angle.

II. PARAMETRIC GEOMETRIC MODEL OF BIOMIMETIC MANTA RAY UNDERWATER GLIDER

Manta rays (Figure 1), under the fen-shaped head, Devil Rays. Is a typical use rajiform mode swimming animals, have two large and powerful pectoral fins. Manta rays rely on flexible pectoral fins swing to push the body swimming, pectoral fins up and down swing wave passes along a flexible pectoral fins, forming thrust push the body forward. As shown in Figure 2, the shape of manta rays could simplify to the similar oval central structure and the triangular wing structure in two parts.

Because of the need to drive the body swimming by pectoral fins, manta rays’ pectoral fins evolved similar triangles. This shape provide sufficient strength for the pectoral fins to resist the momentum when the manta rays gliding, but this shape structure increases the relative wet surface area. Unlike manta rays, underwater glider wing is mainly used to generate lift and improve stability of the glider, using sweep structure can be reduced relative wet surface area, thereby improving the gliding fraction. According to the literature [16], using the sweep structure can improve the stability of the glider. Parametric geometric model of biomimetic manta ray underwater glider is shown in Figure 3. Biomimetic manta ray underwater glider model diagram is shown in Figure 4. Biomimetic manta ray underwater glider shape parameters as shown in Table 1.

![Manta rays](image1)

**Figure 1. Manta rays**

![Simplified shape of manta rays](image2)

**Figure 2. Simplified shape of manta rays**

![Parametric geometric model of biomimetic manta ray underwater glider](image3)

**Figure 3. Parametric geometric model of biomimetic manta ray underwater glider**

![Shape parameters of biomimetic manta ray underwater glider](image4)

**Figure 4. Shape parameters of biomimetic manta ray underwater glider**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Explanation</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>$c_l$</td>
<td>Chord length of the body</td>
<td>1630 mm</td>
</tr>
<tr>
<td>$b_t$</td>
<td>Wingspan</td>
<td>1850 mm</td>
</tr>
<tr>
<td>$R_l$</td>
<td>Leading edge radius</td>
<td>495 mm</td>
</tr>
<tr>
<td>$R_t$</td>
<td>Trailing edge radius</td>
<td>800 mm</td>
</tr>
<tr>
<td>$c_{root}$</td>
<td>Relative width of the wing</td>
<td>980 mm</td>
</tr>
<tr>
<td>$c_{tip}$</td>
<td>Chord length of the wing</td>
<td>290 mm</td>
</tr>
<tr>
<td>$L$</td>
<td>Distance of wing’s tip from front round nose</td>
<td>1300 mm</td>
</tr>
<tr>
<td>$b$</td>
<td>Distance of the body</td>
<td>383 mm</td>
</tr>
<tr>
<td>$a$</td>
<td>Sweepback degrees</td>
<td>32.7°</td>
</tr>
</tbody>
</table>

III. THE STEADY MOTION ANALYSIS OF BIOMIMETIC MANTA RAY UNDERWATER GLIDER

The speed and motion of the Biomimetic Manta Ray Underwater Glider are adjusted by its internal pitch adjusting device and buoyancy regulating device. By adjust the position of the sliding mass inside the pitch adjusting device, the position of overall center of gravity
has been changed. The overall net buoyancy changes through pumping and drainage the water use the buoyancy regulating device. To study on the law of its movement, the situation of steady diving is analyzed for the process of rising and diving of the glider has symmetry. As shown in Figure 5, in order to describe the glider’s movement, two coordinate system have been defined, geodetic coordinate system $E - \xi \eta \zeta$ (inertial coordinate system) and the carrier coordinate system $G - xyz$ (consider the carrier floating center as the origin). The position of the carrier is defined as the position that the origin’s (origin of the carrier coordinate system) position in the geodetic coordinate system. The attitude of the carrier can be determined by the three Euler angles between the carrier coordinate system and the geodetic coordinate system, namely, the pitch angle $\alpha$, yaw angle $\nu$ and roll angle $\phi$.

Figure 5. Force balance of biomimetic manta ray underwater glider

The steady gliding motion is the main form of motion in the process of the biomimetic manta ray underwater glider operation, so most of the working time of the biomimetic manta ray underwater glider is in steady gliding. To establish the dynamic equation of the system in the vertical plane based on the Newton-Euler method [8], the dynamics expression of the Biomimetic Manta Ray Underwater Glider’s motion as follows:

$$
\begin{align*}
\dot{x} &= v_x \cos \theta + v_y \sin \theta \\
\dot{y} &= v_x \sin \theta + v_y \cos \theta \\
\dot{\theta} &= \alpha_2 \\
\dot{v}_x &= \frac{1}{m_1}[-m_x \dot{\alpha}_1 \sin \theta + m_y \sin \theta + (L \sin \alpha - D \cos \alpha - u_x)] \\
\dot{v}_y &= \frac{1}{m_2}[-m_x \dot{\alpha}_1 \sin \theta + m_y \cos \theta - (L \cos \alpha + D \sin \alpha) - u_y] \\
\dot{v}_x &= \frac{1}{m_2}[-mg \cos \theta - z_v \dot{\theta} + (m_{13} - m_{12}) v_x + M_{\alpha 1} - \tau_1 u_1 + \tau_3 u_1] \\
\tau_2 &= \frac{1}{m_{13}} \dot{\alpha}_1 - \dot{v}_x - \dot{\alpha}_2 \\
\tau_3 &= \frac{1}{m_{13}} \dot{\alpha}_1 - \dot{v}_x - \dot{\alpha}_2 \\
\dot{Q}_{1x} &= u_i \\
Q_{1x} &= u_i \\
\dot{m}_1 &= u_v \\
\dot{m}_2 &= u_v \\
\dot{m}_3 &= u_v \\
\dot{m}_4 &= u_v \\
\dot{m}_5 &= u_v \\
\dot{m}_6 &= u_v \\
\end{align*}
$$

(1)

Where is the horizontal displacement and vertical displacement in geodetic coordinate system, $\theta$ is pitch angle, $v_x, v_y$ is the velocity of the glider along the $G x$ axis and the $G y$ axis in the carrier coordinate system, $\omega_\theta$ is the angular velocity of glider rotates on the $G y$ axis, $m$ is the total mass, $m_x$ is the net buoyancy mass, $m_y$ is the quality of pumping and drainage water, $m_z$ is the pitching moment of additional mass along the $G z$ axis and the $G z$ axis in the carrier coordinate system, $u_i$ is the momentum change rate of sliding mass along the $G z$ axis, $u_v$ is the momentum change rate of Ballast load.

As analysis of the steady motion of biomimetic manta ray Underwater Glider, velocity is a constant does not produce added mass force. The resultant force (moment) of the hydrodynamic drag and lift force is equal to the resultant force (moment) of gravity and buoyancy. The glider moves uniformly and linear along a direction. When the biomimetic manta ray underwater glider steady dives, the motion parameters meet the following conditions:

$$
\begin{align*}
v_x &= v_y = \dot{\alpha}_2 = 0 \\
v_x, v_y, \dot{\alpha} &= C \\
r_{\alpha 3} &= r_{\alpha 1} = 0
\end{align*}
$$

(2)

The force balance equation (1) is simplified as:

$$
\begin{align*}
-L \sin \alpha + D \cos \alpha &= m_x g \sin \theta \\
L \cos \alpha + D \sin \alpha &= m_y g \cos \theta \\
mg \cos \theta - z_v \dot{\theta} &= M
\end{align*}
$$

(3)

Where $\alpha$ is the pitch angle, $\alpha$ is the attack angle, $L$ is the lift, $D$ is the drag, $m_x$ is the mass of the net buoyancy($m_x g = \mathcal{B} - \mathcal{G}$), $m$ is the mass of underwater glider, $x_a$ is the displacement of the center of gravity, $M$ is the moment generated by hydrodynamic force rotates on the $G y$ axis.

When biomimetic manta ray underwater glider steady gliding, its attack angle usually less than 15 degrees, thus, Drag can be expressed as quadric expression of attack angle, the lift and torque can be expressed as a linear expression of attack angle[9].

$$
\begin{align*}
D &= (K_{1x} + K_{x} \alpha^2)(v_x + v_y)^2 \\
L &= (K_{1y} + K_{y} \alpha)(v_x + v_y)^2 \\
M &= (K_{1z} + K_{z} \alpha)(v_x + v_y)^2 \\
v &= (v_x + v_y)^2
\end{align*}
$$

(4)
Where $v_1$, $v_3$ is the axial velocity and vertical velocity in the carrier coordinate system, $K_D$, $K_L$, $K_M$ is the quantized coefficient of drag, coefficient of lift, coefficient of moment (subscript "0" represents parameters of linear motion, without "0" represents the parameters that related to the angle of attack).

Determine the relationship between the state parameters (attack angle, pitch angle, velocity) and controlled parameter ($x_G, m_0$), this will provide the basis for the parameter design of the pitch regulation mechanism and the buoyancy regulating mechanism.

The commercial software CFX is used to calculate glider steady dives at velocity of 1knot and 2knot. Under the condition that the attack angle from 0 degree to 10 degree and the interval is 1 degree. The grid is divided into unstructured grids, and the amount is 1.9 million to 2.0 million. Mesh refinement is performed at the boundary layer of the surface of the underwater glider. This can ensure the reasonable amount of the grids, but also reduce the overall amount of the grids, so that the calculating speed can be accelerated without reducing the accuracy. The governing equation for the cases considered in this paper are the RNG $k - \varepsilon$ equations for incompressible viscous flow. Figure 6 to Figure 8 is the hydrodynamic simulation results of biomimetic manta ray underwater glider. Use the least square method to calculate the hydrodynamic parameters of dive gliding model, nondimensionalized results are shown in table 2.

In the case of small attack angle, $\sin \alpha = \alpha$, $\cos \alpha = 1$, there is the relationship between the attack angle $\alpha$, pitch angle $\theta$, velocity $v$ and $x_G, m_0$, as shown in Figure 9 to Figure 11.
As shown in Fig.9, attack angle $\alpha$ decreases with the increasing of the center of gravity displacement, the influence is very small to attack angle, with the changes of net buoyancy. As shown in Fig.10, pitch angle increases with the increasing of the center of gravity displacement, the influence is very small to pitch angle, with the changes of net buoyancy. As shown in Fig.11, velocity increases with the increasing of net buoyancy, the influence is very small to velocity, with the changes of center of gravity displacement.

IV. STEADY MOTION ANALYSIS AND COMPARISON OF THE BIOMIMETIC MANTA RAY UNDERWATER GLIDER WITH CONVENTIONAL UNDERWATER GLIDER

As a new concept of underwater glider, the biomimetic manta ray underwater glider has more prominent features than conventional underwater glider. Lift-to-drag ratio is an important evaluation index for the performance of underwater glider [15], as the lift-to-drag ratio increases, the underwater glider has higher gliding economy. Figure 12 shows the biomimetic manta ray underwater glider has higher lift-to-drag ratio than conventional underwater glider motioned in [8].

Velocity is another important evaluation index for the performance of underwater glider. Figure 13 shows the biomimetic manta ray underwater glider has higher velocity than conventional underwater glider. Figure 14 shows the biomimetic manta ray underwater glider has the highest horizontal velocity at the gliding angle of 27°, while it is 36° of the conventional underwater glider. Which is shown that the biomimetic manta ray underwater glider has the characteristics of high velocity and small gliding angle.
In this paper, the hydrodynamic structure shape of the biomimetic manta ray underwater glider is established with reference to the appearance of manta rays. The hydrodynamic performance of the biomimetic manta ray underwater glider is analyzed through commercial software CFX, and the variation of lift and drag alone with the changing of the net buoyancy and center of gravity position is estimated. From the numerical simulation, the following three conclusions can be reached.

1. Attack angle decreases with the increasing of the center of gravity displacement. The influence is very small to attack angle, with the changes of net buoyancy; Pitch increases with the increasing of the center of gravity displacement. The influence is very small to pitch, with the changes of net buoyancy.

2. Velocity increases with the increasing of net buoyancy. The influence is very small to velocity, with the changes of center of gravity displacement.

3. Due to the blended wing body configuration, the left-to-drag ratio of biomimetic manta ray underwater glider is 200% of conventional underwater glider, faster than the conventional underwater glider. The biomimetic manta ray underwater glider has the characteristics of high gliding speed and small gliding angle.

REFERENCES


