Design and CFD Analysis for a Biomimetic Dolphin-like Underwater Glider

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This paper presents an innovative design concept for a biomimetic dolphin-like underwater glider. As an excellent combination, it offers the advantages of both robotic dolphins and underwater gliders to realize high-maneuverability, high-speed and long-distance motions. As the first step, a skilled and simple dolphin-like prototype with only gliding capability is developed. The hydrodynamic analysis in the glider using Computational Fluid Dynamics (CFD) method is executed to explore the key hydrodynamic coefficients of dolphin-like glider including lift, drag and pitching moment, and also to analyze the dynamic and static pressure distribution. Finally, experimental results have shown that the dolphin-like glider could successfully glide depending on the pitching torques only from buoyancy-driven system and controllable fins without traditional internal movable masses.

Keywords: underwater glider; robotic dolphin; biomimetic robots; CFD.

1. Introduction

Underwater gliders have caught much attention in the last three decades.[1–3] As an excellent autonomous underwater vehicle (AUV), the underwater glider has such astonishing performance in characteristics of long distance, extended duration and low cost which enormously promote the significant and effective applications in huge oceans.

Since the first underwater glider was inspired by Stommel in 1989,[4] various underwater gliders have been developed and successfully applied in scientific research and ocean observatory, like Slocum,[5] Seaglider[6] and Spray.[7] Generally, these gliders always orientate the applications in deep oceans, and could be able to operate in over 1000 m depth and last up to nearly 360 days.[8] Traditional design style brings underwater gliders so many advantages in deep oceans, but reduces their maneuverability, such as fast turn in minor radius. In some complex aquatic environments, high maneuverability is vital for underwater gliders to complete certain missions. Consequently, an excellent underwater glider with both great endurance and high maneuverability should be developed.

This paper provides an innovative design concept for a dolphin-like glider to improve the maneuverability. As an excellent combination of robotic dolphins and underwater gliders, the dolphin-like underwater glider can not only perform a fast and flexible locomotion in dolphin flapping style, but also glide for a long distance depending on its buoyancy-driven system. Besides, owing to its controllable pectoral fins and flattened fluke in horizonal plane, the dolphin-like glider could quickly obtain enough pitching torques to adjust its gliding attitude even without traditional internal moveable masses. Our previous work mainly focused on the mechanical design and locomotion control for robotic dolphins.[9,10] Therefore, we have more confidence in the implementation of dolphin-like motion. By comparison, we more care about the realization of the gliding part. Consequently, a dolphin-like glider prototype is first developed to testify the glide motion. For a better space utilization rate and drag reduction, the dolphin-like glider adopts a well profile from killer whale. The hydrodynamic performance in gliding motion is analyzed by Computational Fluid Dynamics (CFD) method, and key hydrodynamic coefficients including lift, drag and moment are also provided for future dynamic analysis. Finally, the experiments testified that the dolphin-like glider could successfully glide upwards and downwards depending on the pitching torques only from buoyancy-driven system and controllable pectoral fins and flattened fluke, even without traditional internal moveable masses.

The rest of this paper is organized as follows. The mechanical design for the simple dolphin-like glider is described in Section 2. The gliding performance analysis using CFD method is detailed in Section 3. Experimental results and analyses are further offered in Section 4. Finally, conclusion and future work are summarized in Section 5.

2. Mechanical Design of the Dolphin-like Glider

As mentioned above, we have confidence in the mechanical design and motion control for a robotic dolphin, and here only focus on the realization of the gliding motion. So a simple testify prototype for gliding motion is developed. Notice that traditional internal moveable masses are specially removed to highlight that the dolphin-like glider could obtain enough pitching torques from buoyancy-driven system, controllable pectoral fins and flattened fluke.

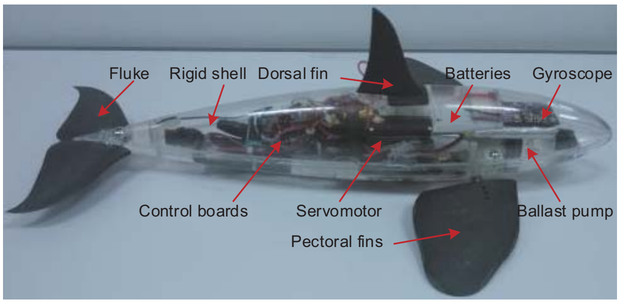

Fig. 1. Mechanical design of the dolphin-like glider.

The mechanical design of the dolphin-like underwater glider is schematically shown in Fig. 1. Generally, the dolphin-like glider is 0.368 m long and weighs 0.752 kg. A rigid well-streamlined body modeled after killer whale is adopted for a better space utilization rate and lift-drag ratio. Notice that pectoral fins and flatten fluke are specially amplified 1.5 times around the center of the mass for larger pitching torques. As shown in Fig. 2, the simple

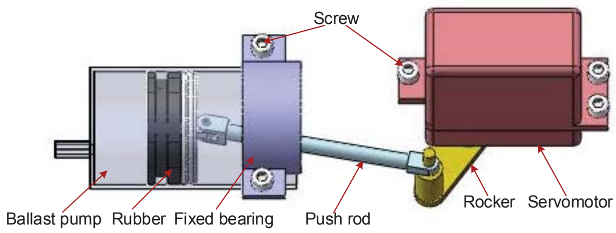

Fig. 2. Mechanical design of the buoyancy-driven system.

and skilled buoyancy-driven system is composed of an injecting syringe, a waterproof rubber, a digital servomotor and a push-pull structure with an aluminium push rod and a copper rocker. When the servomotor working, the copper rocker is turned to drive the aluminium push rod to make the rubber move back and forth in the injecting syringe. Meanwhile, the water in injecting syringe changes the buoyancy of the glider to provide the pitching torques for attitude adjustment.

3. CFD Simulation and Analysis

In this section, CFD methods are employed to analyze the gliding performance of the dolphin-like glider. Because the fins could manually controlled, we need separately compute hydrodynamic coefficients of lifts, drags and pitching moments on dolphin body, pectoral fins and fluke, which could be applied for the hydrodynamic analysis in glide motion. For an accurate and convenient CFD simulation, the commercial software ANSYS 15.0 is employed.[11] ICEM CFD software is adopted as the pre-processing tool to build a mesh for the glider which forms the finite flow domain. Fluent is applied to simulate the flow and pressure distribution around the glider when it is gliding in water.

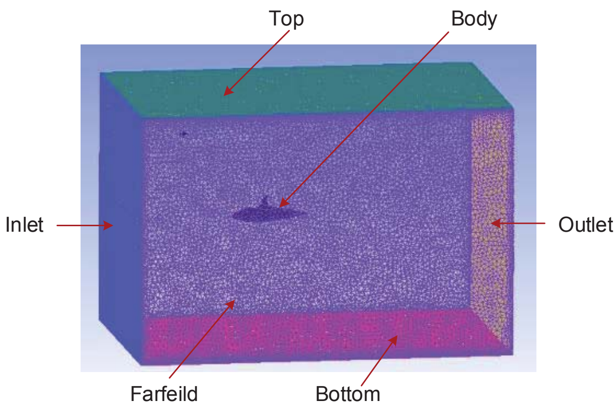

Fig. 3. Boundary conditions for the dolphin-like glider.

In order to gain great adaptability and high quality, an unstructured tetrahedron mesh is formed to describe the flow domain, as shown in Fig. 3. As for the boundary conditions of the CFD simulation for the dolphin's body, the Inlet, two times body length from the nose of the glider, is set as velocity-inlet with $v = 0.1$ m/s, and the Outlet, three times body length from the fluke of the glider, is set as outflow. In order to avoid reflected effect, the Top and Bottom are also set as velocity-inlet with $v = 0.1$ m/s. Other boundaries like Farfeild and Int-fluid are all set as no-flip walls, and the glider surface boundary is also set as no-slip wall. Meanwhile, for a better simulation results, seven prismatic layers are stacked onto the surface mesh. The CFD simulations about the pectoral fins and flattened fluke adopt the similar boundary conditions. In addition, the fluid is supposed as an incompressible and steady one, and $k-\omega$ SST (Shear-Stress-Transport) turbulence model with low-Re corrections is adopted in Fluent simulation.

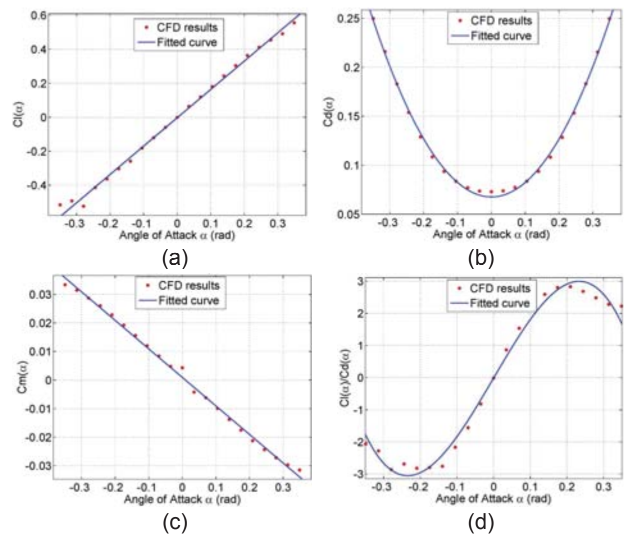

Fig. 4. Hydrodynamic coefficients over AoA of the pectoral fins. (a) Lift coefficient; (b) Drag coefficient; (c) Pitching moment coefficient; (d) Ratio of the lift and drag.

At first, the hydrodynamic coefficients including lift, drag and pitching moment coefficients of the dolphin's body, pectoral fins and fluke have been analyzed for various angles of attack (AoA) α. For example, Fig. 4 shows the coefficients over AoA of the pectoral fins. Notice that the reference area adopts the front one. As conventionally modeled, lift and pitching moment coefficients are linear relationship with the α while drag coefficient is in a quadratic form. The detailed expression is shown in Eq.(1). The hydrodynamic coefficients of the body and fluke have the similar expressions listed as Eq.(2) and Eq.(3).

$$\begin{cases} C_{d_p}(\alpha) &= 1.481\alpha^2 - 0.000357\alpha + 0.6758 \\ C_{l_p}(\alpha) &= 1.667\alpha - 0.003487 \\ C_{m_p}(\alpha) &= -0.09995\alpha + 0.0009239 \end{cases} \tag{1}$$

$$\begin{cases} C_{d_b}(\alpha) &= 1.946\alpha^2 - 0.01843\alpha + 0.2492 \\ C_{l_b}(\alpha) &= 1.406\alpha - 0.01649 \\ C_{m_b}(\alpha) &= -0.1784\alpha + 0.001153 \end{cases} \tag{2}$$

$$\begin{cases} C_{d_f}(\alpha) &= 1.344\alpha^2 - 0.002419\alpha + 0.09103 \\ C_{l_f}(\alpha) &= 1.601\alpha \\ C_{m_f}(\alpha) &= 0.3446\alpha - 0.000524 \end{cases} \tag{3}$$

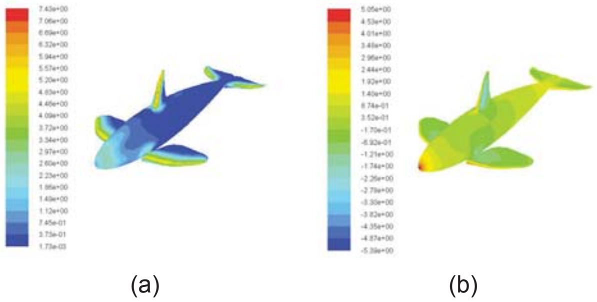

Fig. 5. Pressure contour of the dolphin-like glider. (a) Dynamic pressure; (b) Static pressure.

The analysis in the dynamic and static pressure distribution around the dolphin-like glider are also executed. Fig. 5 separately displays these pressure distribution around the glider. It shows that the highest pressure is at the tip of the glider's nose and the windward side of every fin or fluke, due to the interreaction between the fluid and the dolphin-like glider. These pressures on the rest of the glider surface is both lower because of the smooth flow.

4. Experiments and Discussion

To evaluate the performance of the dolphin-like glider, extensive experiments have been carried out.

The first experiment was designed to testify the downward gliding motion. At the beginning, the glider absorbed about 4.6 g water to keep balance in the surface of the water. The turn angle β between pectoral fins and body was manually changed to explore how the angle β affected the glide speed. When receiving the descending command, the glider began to absorb the other 4.6 g water to glide downwards. According to the experimental results, the glider gained the highest horizontal speed up to 0.096 m/s, when $\beta = 10°$.

The second experiment was carried out to testify the upward gliding motion. Similar with downward glide, the upward gliding motion could be successfully realized through draining away 4.6 g water, as shown in Fig. 6. The glider obtain the highest horizontal speed up to 0.063 m/s.

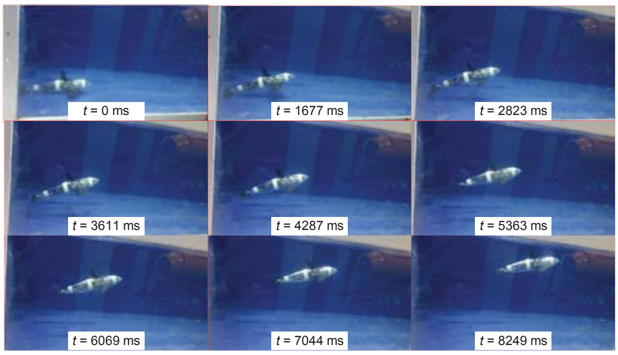

Fig. 6. Snapshot sequence of upward gliding motion.

Traditional underwater gliders usually employ the internal moveable masses to regulate the gliding attitude. Due to moving back and forth, the internal masses often occupy large space that leads to a low space utilization rate. Comparatively, the dolphin-like glider provided in this paper could obtain enough pitching torques from both buoyancy-driven system and controllable fins including pectoral fins and flattened fluke. Moreover, the fluke often provides a considerable pitching moment because of the relative larger moment arm. In this situation, the buoyancy-driven system only need a little volume for water, about $\pm 0.6\%$ of the whole displacement. The volume of the buoyancy-driven system and turn angle of the controllable fins could also be used as controlled input variables for an expected accurate attitude. Moreover, flexible pectoral fins and flattened fluke could bring a quick response to the attitude adjustment.

5. Conclusions and Future Work

In this paper, we have provided a novel design concept of a dolphin-like glider. As an excellent combination, the dolphin-like glider could not only quickly swimming forward in dolphin style, but also quietly glide for a long distance. In order to testify and analyze the gliding motion without the traditional internal moveable masses, a dolphin-like glider prototype has been developed. With the help of CFD simulation, the hydrodynamic characteristics in gliding motion has been analyzed and important hydrodynamic coefficients over the angle of attack and pressure distribution have also been provided for the following dynamic analysis. Experimental results verify that the dolphin-like glider could successfully glide upwards and downwards relying on the pitching torques only from buoyancy-driven system and controllable pectoral fins and flattened fluke, even without traditional internal moveable masses.

The ongoing and future work will focus on the mechanical design and motion control for a real dolphin-like underwater glider possessing both dolphin-like swimming and quiet gliding motion.

6. Acknowledgments

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