# Improved Performance of an Underwater Glider with Passively Rotatable Wings


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***Abstract*—An underwater glider equipped with passively rotatable wings for the use of ocean exploration is presented. The glider is designed to obtain long endurance. We have developed an experimental vehicle as a test facility for an underwater glider with passively rotatable wings. The study is focused on the effect of the wing incidence angle on the gliding distance of the glider. The smaller the gliding angle is, the longer the gliding distance will be. But the gliding angle can't be obtained directly. For there is a relationship between the gliding angle and the lift/drag ratio, we directly measure the lift/drag ratio so as to obtain the relationship between the gliding angle and the wing incidence angle. In this paper, a computational fluid dynamics (CFD) technique is introduced to calculate hydrodynamic forces acting on the glider. A water tank test is also conducted to validate the simulation results, and it is verified that the experimental underwater glider has hydrodynamic characteristics as expected. Having the capacity to glide with a much smaller gliding angle as compared with conventional fixed-wing underwater gliders, the glider with passively rotatable wings has longer gliding range and endurance.**



***Keywords—passively rotatable wings; underwater glider; lift/drag ratio; long endurance***


## I. INTRODUCTION

Nowadays, underwater gliders play more and more important roles in ocean observation. Driven by a buoyancy-engine, these mobile sensor platforms can be deployed for months at a time, travelling thousands of miles. This silent underwater vehicle is easy to maintain and environmental friendly. In this paper, an underwater glider equipped with passively rotatable wings for biophysical and ecosystem monitoring and ocean observation is under development.

There are several earlier studies working on the development of the underwater glider with independently controllable main wings[1-3]. Compared with traditional fixed-wing underwater gliders, the underwater glider with independently controllable main wings has higher performance of motion and can cruise with a much smaller gliding angle. For this type of glider consumes extra energy to control its main wings, it is hard to say there is an increase in its operational duration.

The purpose of this study is to design an underwater glider with improved performance and extended gliding range. We develop an experimental vehicle as a test facility for the underwater glider with passively rotatable wings. Through force analysis, we obtain a function between the gliding angle and the lift/drag ratio. Then we introduce CFD technique to calculate lift and drag in various conditions of glider's attitude and wing incidence angle.

Motion performance of the glider has been surveyed in a swimming pool. The results of the experiment for the lift/drag ratio are compared with the CFD analysis results. The experiment results show that as indicated by the simulation, the glider with passively rotatable wings has better motion performance than conventional fixed-wing glider. This improved performance suggests that the glider with passively rotatable wings can achieve longer range.

## II. PRINCIPLE OF UNDERWATER GLIDERS

The motion mechanism of an underwater glider is the same as its aeronautical counterparts. It uses small changes in its buoyancy in conjunction with wings to convert vertical motion to horizontal, and thereby propels itself forward with very low power consumption. We focus on the forces acting on the glider during its steady motion, which are shown in Fig.1. Let the net weight of underwater glider in air be $\tilde{W}$, the lift be $L$, the drag be $D$, the gliding angle be $\xi$, the attack angle be $\alpha$ and the pitch angle be $\theta$, respectively. Then the underwater glider moves forward with the gliding angle

$$\xi = \tan^{-1}(D / L) \tag{1}$$

Referring to earlier studies [4]and [5], the hydrodynamic forces acting on a glider can be represented in terms of nondimensional force as follows

$$\begin{pmatrix} L \\ D \end{pmatrix} = \frac{1}{2}\rho V^2 S \begin{pmatrix} C_L \\ C_D \end{pmatrix} \tag{2}$$

Where $\rho$ is density of water, $V$ is velocity of the glider, S is the area of wings. Based on physical considerations, such as the symmetry of the outer mold line, the dimensionless coefficients are assumed to have the following dependencies[6]

$$C_L = C_L^{\alpha}\alpha \qquad C_D = C_{D_0} + C_D^{\partial}\alpha^2 \tag{3}$$

The parameter $\alpha$ represents the angle of attack. The parameter $C_{D_0}$ represents the parasite drag due, for example, to skin friction. The parameter $C_D^{\partial}$ represents induced drag coefficient. While hydrodynamic coefficients depend on glider geometry such as the shape and the incidence angle of wings, they also depend on the flow characteristics, which correlate to the Reynolds number[6]. According to above discuss, we know the lift/drag ratio of the glider is

$$\begin{aligned} L/D &= C_L^{\alpha}\alpha / (C_{D_0} + C_D^{\partial}\alpha^2) \\ &= C_L(\alpha, \phi, \mathrm{Re}) / C_D(\alpha, \phi, \mathrm{Re}) \end{aligned} \tag{4}$$

Where $\phi$ is the wing incidence angle, Re is the Reynolds number. From this equation, we know that the dependence of gliding angle on attack angle and wing incidence angle is subtle. We introduce motion simulation and pool experiments to reveal the relationship between the gliding angle, the attack angle and the wing incidence angle.

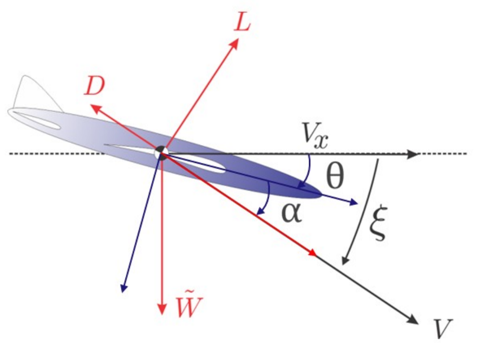



Fig. 1. Free body diagram for an underwater glider

TABLE I. MAJOR PARAMETERS OF THE GLIDER

| | |
|---|---|
| Length | 550mm |
| Breadth( wing span) | 530mm |
| Height | 100mm |
| Diameter of body | 100mm |
| Mass | 4kg |
| Net weight | 0.02kg |
| Wing section, profile | Rectangle |
| Wing chord | 60mm |
| Cruising speed | 0.085m/s |
| Operation depth | 3m |

## III. DESIGN AND MAKING OF AN EXPERIMENTAL UNDERWATER GLIDER

We designed an experimental underwater glider to survey the motion performance of the glider with passively rotatable wings. Table I shows major parameters of the experimental underwater glider.

The glider is equipped with a pair of rotatable wings which can rotate about the wing axis(Fig. 2), and the angle of incidence can be altered from negative 30 to positive 30 degree. As is shown in Fig. 3(a), when the glider is ascending, wings rotate downward under the action of the hydrodynamic forces.

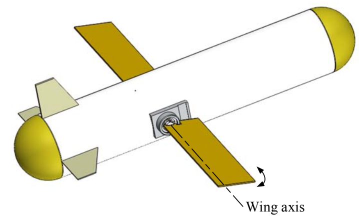
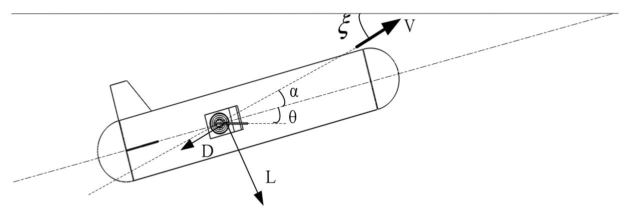
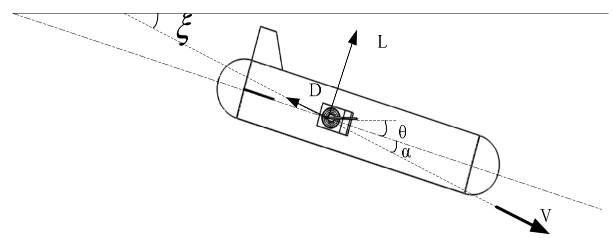



Fig. 2. Underwater glider with passively rotatable wings




(a) Glider ascending




(b) Glider descending

Fig. 3. Movement of wings of the underwater glider

Similarly, as is shown in Fig. 3(b), when the glider is diving, wings rotate upward. There exist a relationship between the lift/drag ratio and the wing incidence angle $\phi$. If $\phi$ is probably chosen, this would lead to greater lift/drag ratio than conventional fixed-wing underwater gliders and improve the motion performance of the glider. The maximum rotation angle of the wings can be set beforehand to achieve the best performance.

Three-dimensional CAD software 'SolidWorks' was introduced to gain 3D model of the experimental underwater glider. Fig. 4 shows an example of 3D model of the glider. The hull of the underwater glider is made of plastic of 4.5mm thick. Wings are made of organic glass of 2mm thick. The weight of the ballast is 1.7kg. It can be moved back and forth to adjust longitudinal position of the centre of mass. Then the glider will nose up or down. There also exist a space of about 200mm in the front portion of the glider for sensors and microcontroller.

## IV. CALCULATION OF HYDRODYNAMIC FORCES BY CFD ANALYSIS

The CFD (Computational Fluid Dynamics) analysis software ‘Fluent’ was introduced to calculate the hydrodynamic forces acting on the glider under various conditions. Fig. 5 shows the unstructured grid of the computational domain. The modeling was assumed to be three-dimensional within a steady flow fluid domain. Continuity equation and N-S equation were used for governing equation. The finite volume method was adopted along with the SIMPLE algorithm for pressure-velocity coupling. To model the turbulence, turbulent $k-\varepsilon$ model was adopted. Computational grid used here was C-O unstructured grid comprised of about two million cells. The mean grid quality was 0.75(0 presents the worst quality, 1 presents the best quality). Fig. 6 shows an example of the pressure distribution around the glider during diving.

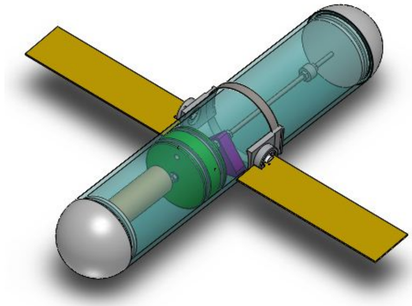


Fig. 4 An example of 3D model of the glider

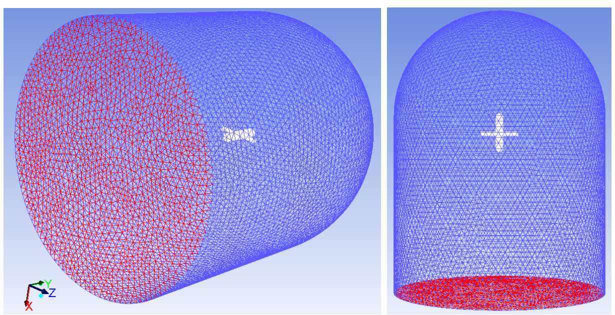


Fig. 5. The unstructured grid of the computational domain.

Hydrodynamic forces acting on the underwater glider were calculated under the following conditions,

1) The velocity of the glider was 0.085m/s.

2) The angle of incidence of the wings to the body was fixed to 0 degree and the angle of attack of the body against water flow was altered from 0 to 4 degree, considering as a glider with fixed wings.

3) The angle of attack of the body against water flow was fixed to1,2 and 4 degree respectively, and the angle of incidence of the main wings to the body was altered from 2 to 28 degree by 2 degree, considering as a glider with passively rotatable wings.

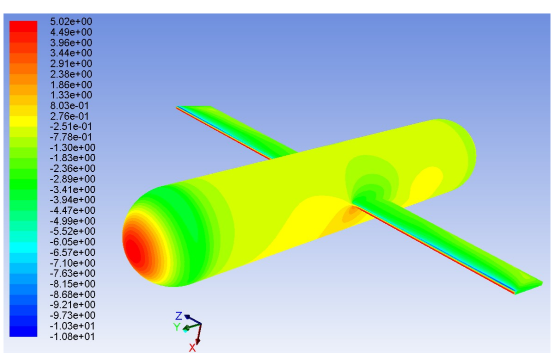



Figure 6. Pressure distribution at V = 0.085 m/s, angle of attack is 4 degree, angle of incidence for the wings is 8 degree.

Lift coefficient, drag coefficient and lift / drag ratio obtained from CFD analysis are illustrated in Figs.7-9. Lift and drag are nondimensionalized by $\rho V^2 S/2$. Fig. 7 shows that the increase of wing incidence angle results in the increase of lift coefficient on the early stage. Then the lift coefficient tend to be a constant. Fig. 8 shows that a big wing incidence angle results in a greater drag coefficient. From Fig. 9, we learn that there is a quadratic function relationship between the lift/drag ratio(the gliding angle) and the wing incidence angle. The lift/drag ratio has a maximum value, which means a minimum value of gliding angle, while the wing incidence angle is in the range of 4~10 degree. We can set this value to be the upper limit of wing incidence angle. Then the gliding distance of the glider will reach its maximum value. Fig. 9 also shows that when the wing incidence angle is in the range of 0~12 degree, the life/drag ratio is greater than the value when wing incidence angle is 0 degree. It means that gliders with passively rotatable wings have better motion performance than conventional fixed-wing gliders.

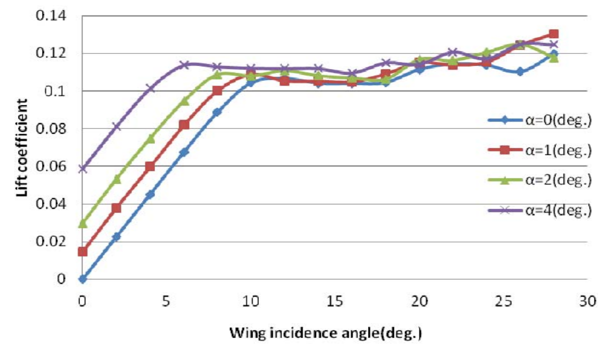



Fig. 7. Non-dimensional lift versus wing incidence angle.

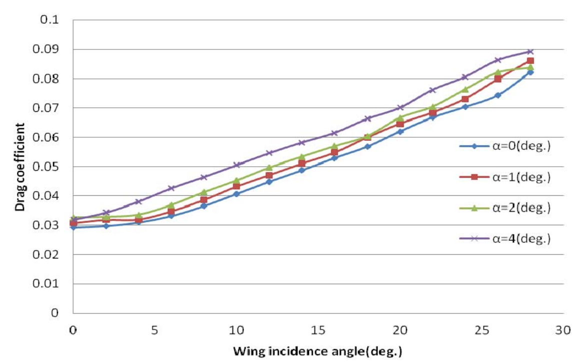



Fig. 8. Non-dimensional drag versus wing incidence angle.

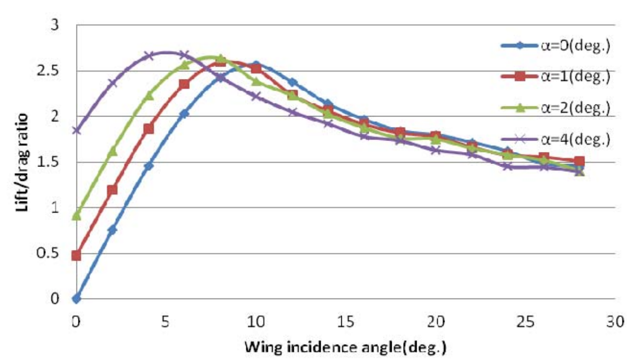



Fig. 9. Lift / drag ratio versus wing incidence angle.

## V. MOTION PERFORMANCE OF THE UNDERWATER GLIDER

A water tank test was conducted to clarify the characteristics of the 'underwater glider with passively rotatable wings' in comparison with a traditional 'underwater glider with fixed wings'. Observation of the motion was conducted at the swimming pool (Length * Breadth * Depth = 50.0m * 20.0m * 1.75m) of Zhejiang University(Fig. 10). The net weight of the glider was 0.02kg. When the glider was released, it commenced diving with the pitch angle being 20 degree. The glider dived in a series of experimental conditions with the wing incidence angle varying from 0 to 28 degree (when the wing incidence angle is set to be zero, it is the case of fixed-wing gliders). The horizontal gliding displacement was measured, and the diving motion of the glider with different wing incidence angle was recorded by a video camera. According to the horizontal displacement of the glider, its lift/drag ratio was obtained. The relationship between the lift/drag ratio and the wing incidence angle is shown in Fig. 11.

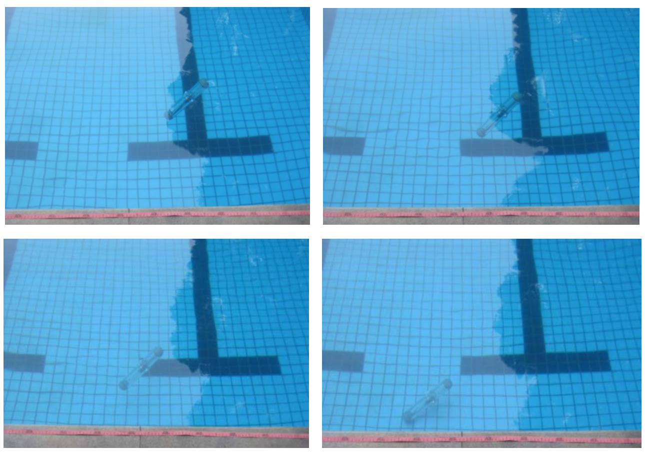


Fig. 10. Water tank test of the glider

The water tank test results are approximately consistent with the CFD analysis results. The lift/drag ratio(the gliding angle) and the wing incidence angle are related in quadratic function as the same. The lift/drag ratio has a maximum value as the wing incidence angle increases. When the wing incidence angle is set to be certain value, the glider can gain the least gliding angle so as to acquire the longest range. From the experiment results, we can infer that the best wing incidence angle for gliding is 6 degree. It is accordance with the simulation results that there is a maximum of lift/drag ratio while the wing incidence angle is in the range of 4~10 degree. Then the best wing incidence angle is set to be the maximum rotation angle of the wings. In this case, the gliding angle will gain its minimum value, and the glider will obtain the longest operational duration.

There is a deviation between the results of water tank test and CFD analysis. The reason for the deviation is that the glider doesn't not reach steady state, as the swimming pool is shallow. If the swimming pool is deep enough, the experimental results will be more relevant with the CFD analysis results.

The experiment results also show that the glider with passively rotatable wings has better motion performance than

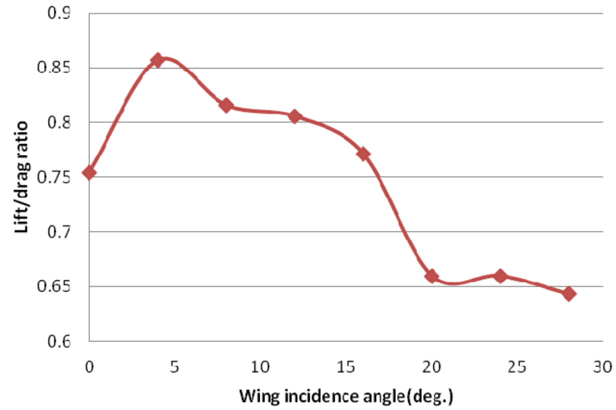



Fig. 11. Experimental results

conventional fixed-wing glider, as indicated in the simulation. This improved performance suggested that the glider with passively rotatable wings can achieve longer range than conventional fixed-wing glider.

## VI. CONCLUSION

This paper deals with the force analysis of an underwater glider with passively rotatable wings. The computational fluid dynamics (CFD) technique has been applied to calculate the hydrodynamic forces acting on the glider. Results of the gliding simulation indicate that the lift/drag ratio(the gliding angle) and the wing incidence angle present quadratic function relation. The simulation results have been compared with the water tank test results. They are approximately correspond with each other. The lift/drag ratio has a maximum value as the wing incidence angle increases. Then the glider can attain the least gliding angle so as to acquire the longest range. An underwater glider with passively rotatable wings is shown to be able to glide with a small angle when the angle of incidence for the main wings is set appropriately, which suggests that it can achieve longer range than conventional fixed-wing glider.

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