A Lab-Scale Underwater Glider With Flexible Camber Trailing Edge Wings

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A lab-scale underwater glider with flexible camber trailing edge wings

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Abstract: Wings are the main source of lift for the underwater gliders (UGs), and play a decisive role in the motion performance of UGs. A lab-scale UG with flexible camber trailing edge wings was proposed and developed to investigate influences of the trailing edge of the wings on the motion performance of UGs. The flexible deformation of the trailing edge was realized by the steer-by-wire actuator. Test results showed that the trailing edge of the wing can realize the maximum upward/downward sloping angles of $+16^{\circ}/-16^{\circ}$. Combining computational fluid dynamics simulations and tank experiments, the glide efficiency and stable margins of the lab-scale UG with variable camber trailing edge wings were obtained. Results showed that the angles of attack corresponding to the minimum lift-to-drag ratios were all negative in cases of downward sloping, and those were all positive in cases of upward sloping. Moreover, the suitable camber of the trailing edge, i.e., downward-sloping trailing edge on descending glides and upward-sloping trailing edge on ascending glides, can not only greatly improve glide efficiency, but also benefit the flight stability. The lift-to-drag ratios of the lab-scale UG with appropriate variable camber trailing edge wings (i.e., on descending glide with downward-sloping trailing edge, and on ascending glide with upward-sloping trailing edge) can increase by at least 10% compared with those with symmetric airfoil.

Key words: lab-scale underwater glider; flexible camber trailing edge; flexible actuator; glide efficiency; motion stability

Declarations

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Authors' contributions

- (1) Yuhong Liu is in charging of the design scheme of the lab-scale underwater glider with flexible trailing edge wings, organizing and writing the manuscript.
- (2) Shixun Xu was in charge of designing and manufacturing the lab-scale underwater glider with

flexible trailing edge wings, and conducting the experiments.

(3) Shan Tian completed the work of the computational fluid dynamics simulation.

(4) Hongwei Zhang gave the guidance and experimental supports in developing the lab-scale underwater glider.

(5) Shihan Deng assisted in the control system debugging and experiments.

(6) Shuhe liu assisted in experiments and data processing.

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1 Introduction

The buoyancy-driven underwater glider (UG) is one of the novel underwater mobile observation platforms with advantages of low cost, low noise, long endurance and long range, which makes it widely applied in ocean observation and monitoring missions [1-3]. The technology and theory of the purely buoyancy-driven UG have become mature gradually, and some commercial products, such as Slocum [4], Seaglider [5], Spray [6], Petrel [7] and Sea-wing [8], have been used in engineering operations since the concept of the UG was proposed in 1989 [9]. Due to that the purely buoyancy-driven UG has a low glide speed (usually less than 1 knots) and poor maneuverability, researchers developed a hybrid UG driven by a combination of buoyancy and propeller to improve the performance of glide speed and maneuverability. Typical examples of hybrid UGs are Slocum AUV [10], Folaga [11], Tethys [12], AutosubLR [13], Sterne [14] and Petrel-II [15]. Moreover, the integration of the propeller expands the motion mode of the hybrid UGs so that the UGs can achieve depth-keeping motion like autonomous underwater vehicles (AUVs). However, the hybrid UGs are easy to lose stability at high glide speed, so some researchers attempted to change the hydrodynamic shapes of the hybrid UGs to match the high-speed glide. Current researches on variable hydrodynamic shape mainly focus on the variable wings, which allow the UGs more adaptable to the environment and further expand the applications of the UGs in various complex marine environments [16-18].

Wings of the UGs provide the main source of lift. The airfoil, structure parameters and layout of the wings will affect the hydrodynamic distribution around the UGs, and play a decisive role in the flight performance. Studies on the optimization of wing structure parameters, wing layout, and the mechanism

design of the variable wings were focused on improving the performance of wings. Arima [19] designed an experimental UG with variable wings through independently controlling the angles of attack of the wings. Wu et al [20] analyzed effects of the layout, chord length, sweep angle and aspect ratio of wings on the flight efficiency and motion stability of a hybrid underwater glider (HUG) using orthogonal test. Wu's research showed that the glide efficiency, i.e., in terms of lift-to-drag ratio, of the UG is significantly influenced by the chord length and aspect ratio of the wings, and increases with increasing of them; the motion stability is greatly influenced by the sweep angle with the law of inverse proportion. Based on Wu's research results, Yang et al [21] designed a variable wing which can realize changes of aspect ratio, sweep angle and angle of attack through synthesizing a planar five-bar mechanism and a planar bi-parallelogram mechanism. National Oceanography Center of UK developed an underwater vehicle named AutosubLR [22] with a pair of wings made in sections to balance the net buoyancy. Moreover, the angle of attack and location of the wings of AutosubLR can be adjustable to adapt different mission characteristics. Tian et al [23] proposed a hybrid-driven UG model with controllable wings, and investigated effects of angle of attack of wings on maneuverability of the glider through motion simulation. Isa et al [24] studied the hydrodynamics estimation and motion control of an HUG model with controllable wings and rudders. Gong et al [25] designed a flat wing model with a high lift-to-drag ratio according to the influence of the span, aspect ratio, root-tip ratio, sweep angle and layout on flight efficiency of a laboratory-scale UG. Zhao et al [26] proposed the concept of a passive elastic wing to improve the stability of the UG.

Particularly, in the last five years, the applications of intelligent materials and flexible structures in underwater robots [27, 28] have widened the vision and provided a new way for the wing research. Xu et al [29] proposed the concept of variable camber trailing edge wing and demonstrated its feasibility by studying effects of the airfoil on flight efficiency of the UG. Angilella et al [30] designed a variable-camber wing driven by thermocline activated shape memory alloys (SMAs), and pointed out that the variable-camber wing can reduce energy consumption required to trim the UG, so as to improve its endurance and range. Li et al [31] proposed a conceptual model of underwater glider with a pair of bio-inspired hydro wings, and numerically investigated the hydrodynamic performance of the glider. In the present work, based on the achievement in literature [29], a flexible camber trailing edge wing based on NACA0012 airfoil was developed using the steer-by-wire actuator to improve the flight performance, especially the glide efficiency of UGs. Meanwhile, a lab-scale underwater glider was developed to investigate effects of the flexible camber trailing edge wings on flight performance of the UG.

The remainder of the paper is organized as follows. Section 2 describes the system composition of the lab-scale underwater glider and designing of the flexible camber trailing edge wing. Section 3 is focused on the evaluation index for the flight performance of the UG, and deduces a cost-saving discriminant formula for motion stability of the glider with variable wings. Section 4 presents the method of the computational fluid dynamics (CFD), including the study scheme, numerical modeling, meshing, boundary conditions and solution setting, and results discussions on the effects of the variable camber trailing edge wings on flight performance of the glider. Tank experiments are in Section 5 and a brief summary in Section 6.

2 The lab-scale UG with flexible camber trailing edge wings

2.1 Structure and main specifications of the lab-scale UG

The lab-scale UG was designed to investigate flight performance of underwater gliders with flexible wings. Main body of the glider is similar in geometry to that of “Petrel-II” [32] UG developed by Tianjin University with the same hydrodynamic profile and length-diameter ratio of 9.8. Table 1 shows the main specifications of the lab-scale UG.

Table1 The main specifications of the lab-scale UG

Particulars	Values
Length	980 mm
Diameter	100 mm
Wing section	NACA 0012
Wing span	480 mm
mass	5.23 kg
Adjustable buoyancy	-0.9~+0.9 N
Maximum speed	0.55 m/s
Operation depth	5 m

The lab-scale UG involves five subsystems: the main body (including the pressure hull, nose and tail), the buoyancy subsystem, the control subsystem, the flexible wings and the tail fin (Fig. 1). The main body is a low drag hydrodynamic profile with the cylindrical pressure hull, ellipsoid nose and Myring-shaped tail. The buoyancy subsystem can be used not only to adjust the buoyancy of the glider, but also to regulate its pitch attitude. Changes in buoyancy can be realized by water suction and drainage of three syringes driven by a screw-nut pair. In this way, the gravity center of the glider can then be changed simultaneously and the pitch motion of the glider in vertical plane can be also realized. Missions of the control subsystem are to control the pitch motion of the glider, change camber of the trailing edge, record data collected by sensors, and provide energy with rechargeable lithium battery. The core unit of the

control circuit is a single chip microprocessor of Arduino UNO R3. The flexible wings are the main providers of the lift, and can realize continuous camber change of the trailing edge through flexible actuator. The flat tail fin is used for keeping stability of the glider.

Figure 1 Layout of the lab-scale underwater glider

2.2 The flexible camber trailing edge wing

According to literature [29], the NACA 0012 airfoil was chosen as the basic airfoil of the wings, considering the requirements for lift-to-drag ratio and assemble space. The main structure parameters of the wings are listed in Table 2.

Table 2 Structure parameters of the flexible wings

Particulars	Values
Unilateral wingspan	200.0 mm
Root chord	105.0 mm
Tip chord	60.0 mm
Root thickness	12.0 mm
Tip thickness	7.2 mm
Sweep angle at the leading edge	30°
Sweep angle at the trailing edge	20°

For convenience of assembling and adjusting the trailing edge, the designed flexible wing is divided into six parts shown in Fig. 2: the leading edge, the trailing edge, the root block, the tip block, the root linkage and the tip linkage. The root block, which is the root of the wing, is used for wiring signal lines and connecting the main body and root linkage, while the tip block, which is the tip of the wing, is used to connect the leading edge and the tip linkage. The root and tip linkages are used to connect the trailing edge through the rotating pairs for adjusting trailing edges. The leading edge with partial airfoil is connected with the root and tip blocks through the wedges. Surface of the flexible wing is covered with

flexible skin (Fig. 2(c)) and can deform with changes of the camber of the trailing edge, so that different wing shapes can be achieved.

Figure 2 Structure of the flexible wing with steer-by-wire actuator for deforming the trailing edge

Considering the limited space inside the wing and the flexible deformation of the trailing edge, the actuation mode driving the trailing edge deflection was determined to be flexible actuation preferably. The current mainstream flexible actuation used in soft robotics [27, 33-37] is mainly based on the smart-materials, including pneumatic artificial muscle (PAM) actuator [33, 34], shape memory alloy (SMA) actuator [35], electro-active polymer (EAP) actuator [36], and chemical stimulation actuator [37]. However those actuators based on smart-materials either require a huge power and gas supplies or is unable to meet activation temperature requirements, preventing them from being used in underwater vehicles. It is obvious that the chemical stimulation actuator is also not available in the current design. Although the EAP actuator has a good application prospect in underwater vehicles, it is difficult to meet the large driving force requirement of realizing deformation of the trailing edge of the wing. Therefore, a steer-by-wire actuator, which is widely used in conventional robots and can realize accurate control, was proposed to be used as the actuator.

The steer-by-wire actuation. A steer-by-wire actuator (Figs. 2) was designed to drive the trailing edge deformation. The steer-by-wire actuator, including a common small steering engine with the model of SG90 and a flexible wire applied with a sewing thread with diameter of 0.5 mm in the present work, was

placed in the space between the leading edge and trailing edge (Fig. 2(a)). One end of the flexible wire was fixed at the front end of the trailing edge, and the other end was wrapped around the output end of the steering engine. When the output end of the steering engine turns, the tighten wire makes the trailing edge turn. Different cambers of the trailing edge can be obtained by adjusting the output angle of the steering engine. The trailing edge can realize ideal deformation (Fig.3). The maximum upward/downward sloping angles can be $+16^\circ/-16^\circ$, corresponding to the $+8\text{ mm}/-8\text{ mm}$ deflections of the trailing edge.

Figure 3 Deformations of the trailing edge driven by steer-by-wire actuator

3 The evaluation index of flight performance

Flight motion of legacy UGs [38], i.e., the purely buoyancy-driven UGs, follows the sawtooth path in vertical plane. The hybrid UGs [32] driven by buoyancy and propeller can not only move along sawtooth path in vertical plane but also perform depth-keeping navigation in horizontal plane like autonomous underwater vehicles (AUVs) do. For the evaluation indexes of flight performance in vertical plane, the glide velocity, the glide efficiency and the motion stability are mainly considered. For those in horizontal plane, the motion stability and the maneuverability are commonly involved. The lab-scale UG designed in our work is a type of legacy UG. Therefore, the glide velocity, glide efficiency and motion stability are critical indexes determining the flight performance of the glider and concerned in our present work.

3.1 Glide velocity

According to the theory of legacy underwater glider, the horizontal velocity in steady glide stage can be expressed as [32]

$$u = \sqrt{2B_b \cdot \sin(\gamma) / \rho C_D A_D} \cdot \cos(\gamma) \quad (1)$$

where γ is the glide angle, B_b is the net buoyancy, $B_b = \rho g V_b$, ρ is the density of the water, g the gravity acceleration, V_b the net displacement volume, C_D the drag coefficient of the glider, and A_D the cross-sectional area of the glider. To the present lab-scale glider, $\rho = 9.8 \text{ kg/m}^3$, $C_D = 0.47$, $A_D = 0.007854 \text{ m}^2$.

According to Eq. (1), for a designed glider, the glide velocity of the glider just depends on the net buoyancy or the net displacement volume and the glide angle. When the net buoyancy or the net displacement volume is given, the horizontal velocity is only effected by the glide angle, and the maximum horizontal velocity can be obtained at a glide angle of 35° . The change of horizontal velocity of the lab-scale UG with net displacement volume at different glide path angles in steady glide can be obtained, as shown in Fig. 4. It can be seen from Fig. 4, the max horizontal velocity of the glider is 0.428 m/s when the glide angle is 35° and the net displacement volume is 90 ml.

Fig.4 Change of the horizontal velocity with the net displacement volume at different glide path angles

3.2 Glide efficiency

The energy consumption is a main concern and is always expected to be the least in the UG design. The energy consumption, which is evaluated by the index of transport economy, is related with the hydrodynamic shape, glide speed and path of the glider, pumping work of the buoyancy system, motor work of the attitude system, the control system and work of task sensors. By contrast, the hydrodynamic shape, glide speed and path decide the lift-to-drag ratio (L/D) of the glider, which is a measure of glide efficiency. Studies [38] show that the transport economy of the glider would improve three fold if the glider travels at an optimal glide speed and path. Moreover, the reverse of L/D is the specific energy consumption $E_e = DU/Bu$, where U is the glide velocity, B is the net buoyancy, and u is the horizontal velocity. That is to say, bigger L/D means greater energy efficiency.

3.3 Motion stability

3.3.1 Stability margin of UG with symmetrical airfoil

When there is an transient external disturbance, the positional force $Y(\alpha)$, positional moment $N(\alpha)$, rotational force $Y(r)$, and rotational moment $N(r)$ acting on the glider in vertical plane are illustrated in Fig. 5, where E-XYZ is the Earth-fixed frame and o-xyz is the body-fixed frame whose origin O coincides with the buoyancy center of the vehicle.

Figure 5 The positional force/moment and rotational force/moment acting on the glider in vertical plane

Based on the theory from literatures [39] and [40], the stability margin of the glider with symmetrical airfoil can be expressed as,

$$G_r = 1 - \frac{\overline{L}_\alpha}{\overline{L}_r} = 1 - \frac{T_Z^\alpha [V_T (C_Y^r - \mu) + \mu y_G r]}{C_Y^\alpha V_T T_Z^r} \quad (2)$$

where G_r is an index to evaluate the motion stability of UG, and $\overline{L}_\alpha$ and $\overline{L}_r$ denote the dimensionless arms of positional force and rotational force, respectively. From Fig. 5, it gives $\overline{L}_\alpha = \frac{N(\alpha)}{L * Y(\alpha)}$ and

$\overline{L}_r = \frac{N(r)}{L * Y(r)}$. L is the characteristic length of the glider. T_Z^α and T_Z^r are the viscous hydrodynamic

moment coefficients related to angle of attack α and rotation speed r , respectively. C_Y^α and C_Y^r are the hydrodynamic coefficients related to angle of attack α and rotation speed r , respectively. V_T is the

glide velocity, y_G the component of CG (Center of Gravity) of the glider in y-axis, μ dimensionless

mass and expressed as $\mu = \frac{2m}{\rho SL}$, ρ the seawater density, and m and S the mass and cross

sectional area of the glider, respectively.

3.3.2 Improved equation of stability margin for UG with asymmetrical airfoil

To achieve the motion stability index G_r , a lot of calculations for the hydrodynamic coefficients of the UG have to be conducted. All the calculations should be repeated when the hydrodynamic shape of the vehicle is changed. To lower the cost of computing hydrodynamic coefficients, an improved equation of stability margin for the UG with variable airfoil was derived from Eq. (2).

When the wings with asymmetrical airfoil, such as the variable camber, suffer a small disturbance, the damping force and moment of the wings can be divided into two parts: one is provided by the symmetrical airfoil, the other is related to the degree of deformation of the airfoil section. Given the damping force $F(\delta)$ and moment $M(\delta)$ related to the camber angle δ of the trailing edge, the total damping force and moment can be expressed as $Y(r) + F(\delta)$ and $N(r) + M(\delta)$, respectively, according to the superposition principle. Then arm of the rotational force of the glider with variable camber trailing edge wings is given

$$L_{r\delta} = \frac{N(r) + M(\delta)}{Y(r) + F(\delta)} \quad (3)$$

Actually, the damping force $F(\delta)$ and moment $M(\delta)$ represent the differences between the hydrodynamics forces and moments after and before deformation of the wing, respectively. The dimensionless arm of the rotation force can be

$$\overline{L_{r\delta}} = \frac{L_{r\delta}}{L} \quad (4)$$

Substituting Eqs. (3) and (4) into Eq. (2), the stability margin of the glider with variable camber trailing edge wings can be obtained, as

$$G_{r\delta} = 1 - \frac{\overline{L_\alpha}}{\overline{L_{r\delta}}} = 1 - \frac{T_Z^\alpha \left[V_T (C_Y^r - \mu) \cdot r + \mu y_G r^2 + e F(\delta) \right]}{C_Y^\alpha (V_T T_Z^r \cdot r + e M(\delta) / L)} \quad (5)$$

where $e = \frac{2}{\rho S L}$.

Equation (5) is the improved stability margin of the glider with variable camber trailing edge wings. When the hydrodynamic shape of the wings changes, the hydrodynamic force/moment of the deformed wing, instead of the whole glider, will be calculated. Therefore, the complexity and computational cost of the model are greatly reduced.

According to literature [39] and Equ. (5), the criterion for motion stability of the UG can be described as:

- (1) When $T_z^\alpha < 0$, $G_{r\delta} > 1$, the motion is statically stable.
- (2) When $0 < G_{r\delta} < 1$, the motion is dynamically stable.
- (3) When $G_{r\delta} < 0$, the motion is unstable.

4 Calculation and discussion for the evaluation index

4.1 Scheme

Against the proposed lab-scale UG with flexible camber trailing edge wings, the glide efficiency and motion stability of the glider were investigated at different camber angles of the wing's trailing edge and different angles of attack based on the computational fluid dynamics (CFD) simulation.

The camber is at the $0.85l$ of the wing's chord length l , and the camber angles are $\pm 5^\circ$, $\pm 10^\circ$, $\pm 15^\circ$, $\pm 20^\circ$, $\pm 25^\circ$ and $\pm 30^\circ$, respectively, where the signs “+” and “-” indicate the upward sloping and downward sloping of the trailing edge (Fig. 6). The angle of attack ranges from -10° to $+10^\circ$ in steps of 1° with the positive values representing descending glides and the negative ones representing ascending glides.

Figure 6 Diagram of the airfoils with different trailing edges

4.2 Numerical modeling

4.2.1 Modeling of the glider

The computational domain was chosen as a cylinder (Fig. 7) with the diameter of 5 m and the length of $10L$, where L is the characteristic length of the lab-scale UG. The axis of the computational domain coincides with that of the lab-scale UG. The upstream boundary was set as $4L$ away from the leading end

of the glider, and the downstream boundary was $5L$ away from the trailing end of the glider. The outer surface of the glider was set as solid wall, and no-slip boundary was used for velocity components on the solid wall. The inlet boundary was velocity-inlet with the flow velocity of 0.5 m/s , while the outlet boundary was outflow. The cylindrical surface of the domain was set as the symmetric boundary. The unstructured grids were applied in the fluid computational domain. The surface grids on the main body, wings and other parts of the glider were refined to 5 mm , 3 mm and 2 mm , respectively. Meanwhile the size function was used to define the grids in the boundary layer around the glider. Grid height in the first layer was set as 0.62 mm with the growth rate of 1.15 in 6 boundary layers.

Figure 7 Numerical modeling of the glider

4.2.2 Modeling of the wing

In order to obtain $F(\delta)$ and $M(\delta)$ provided by the flexible camber trailing edge wings, hydrodynamic forces of the wing should be calculated independently. The computational domain (Fig. 8(a)) was a 2D rectangular region with the width of $3.5l$ and the length of $7l$, where l is length of the wing chord. The upstream boundary was set as $3.5l$ away from the leading end of the wing, and the downstream boundary was $2.5l$ away from the trailing end of the wing. The outer surface of the wing was set as solid wall, and no-slip boundary was used for velocity components on the solid wall. The inlet boundary was velocity-inlet with the flow velocity of 0.5 m/s , while the outlet boundary was outflow. The top and bottom edges of the domain were set as the symmetry boundary. Because regular mesh generation is beneficial to improving calculation speed and accuracy, 2D topology grids were applied in the rectangular domain. All the elements were quadrangular, as shown in Fig. 8. The subregional meshing strategy (Fig. 8(b)) was adopted to balance the accuracy and cost of the calculation.

4.3 Solution

The calculations were performed using the commercial CFD code of ANSYS-FLUENT. The fluid is assumed as incompressible continuous medium with the density and viscosity of 1000 kg/m^3 and $0.001003 \text{ kg/(m}\cdot\text{s)}$, respectively. The Reynolds number of the glider model is 4.89×10^5 . For the wing with chord length of 60 mm, the Reynolds number is around 2.99×10^4 . The SST $k - \omega$ turbulence model was chosen to close the Navier-Stokes equation. The finite volume method was used to discretize the governing equations, and the second-order upwind scheme was adopted to discretize the momentum equations. Accuracy of the CFD calculation has been verified in literature [41].

(a) The computational domain and boundary conditions

(b) Grids around the airfoil

Figure 8 Numerical modeling of the airfoil

4.4 Results and discussion

4.4.1 Glide efficiency

The lift-to-drag ratios (L/D) of the lab-scale UG with different trailing edge wings at different angles of attack α are shown in Fig. 9. It can be seen that the curves for the lift-to-drag ratios of the glider with symmetrical airfoil are symmetric with respect to 0° angle of attack. At 0° angle of attack, where the lift-to-drag ratio is the lowest, the glider has the least glide efficiency. However, for the gliders with asymmetric

airfoil, such as wings with upward or downward sloping trailing edge, their minimum lift-to-drag ratios are not found at $\alpha=0^\circ$. In the cases of upward-sloping trailing edge of the wings, the minimum lift-to-drag ratios appear in the range of positive angles of attack. Moreover, the larger upward-sloping camber angle of the trailing edge, the larger positive angle of attack corresponding to the minimum lift-to-drag ratio (Fig. 9(a)). On the contrary, in the cases of downward-sloping trailing edge of the wings, the minimum lift-to-drag ratios appear in the range of negative angles of attack. Moreover, the larger downward-sloping camber angle of the trailing edge, the larger absolute value of the negative angle of attack corresponding to the minimum lift-to-drag ratio (Fig. 9(b)). For the investigated cases of camber angles of $\pm 5^\circ$, $\pm 10^\circ$, $\pm 15^\circ$, $\pm 20^\circ$, $\pm 25^\circ$ and $\pm 30^\circ$, the angles of attack corresponding to the minimum lift-to-drag ratios are around $\pm 1^\circ$, $\pm 3^\circ$, $\pm 4^\circ$, $\pm 5^\circ$, $\pm 6^\circ$ and $\pm 7^\circ$, respectively. The phenomenon that the minimum lift-to-drag ratios are not at the 0° angle of attack indicates that the UGs with variable camber trailing edge wings have better flight efficiency than those with symmetrical airfoil, and they can get a better lift-to-drag ratio even at a smaller angle of attack.

Figure 9 Lift-to-drag ratios (L/D) of the glider with variable camber trailing edge wings at different angles of attack α

Also from Fig. 9, lift-to-drag ratios increase with the absolute value of angles of attack firstly, and then decrease from a certain angle of attack. The angles of attack corresponding to the maximum lift-to-drag ratios, the max angles of attack for short, increase with the camber angle of the trailing edge. For the case of symmetric airfoil, the max angles of attack are about $\pm 9^\circ$, while for cases of asymmetric airfoil, the max angles of attack are less than $\pm 9^\circ$. The larger camber angle of the trailing edge, the smaller

max angle of attack. For the investigated cases of camber angles of $\pm 5^\circ$, $\pm 10^\circ$, $\pm 15^\circ$, $\pm 20^\circ$, $\pm 25^\circ$ and $\pm 30^\circ$, the max angles of attack are around -8° , -7° , -6° , -5° , -4° and -4° , respectively.

For the case of upward-sloping trailing edge in Fig. 9 (a), when $\alpha \leq 0^\circ$, the lift-to-drag ratio increases with the upward-sloping angle, which has the opposite tendency when $\alpha \geq 0^\circ$. Moreover, when $\alpha \leq 0^\circ$, all the lift-to-drag ratios of the glider with upward-sloping trailing edge wings are better than those of the ones with symmetric airfoil, while the upward-sloping trailing edge wings perform worse than the symmetric airfoil when $\alpha \geq 0^\circ$. For the cases of downward-sloping trailing edge shown in Fig. 9(b), the opposite is true. When $\alpha \geq 0^\circ$, the lift-to-drag ratio increases with the downward-sloping angle, while it has the opposite tendency when $\alpha \leq 0^\circ$. Moreover, when $\alpha \geq 0^\circ$, all the lift-to-drag ratios of the glider with downward-sloping trailing edge wings are better than that of the one with symmetric airfoil, while the downward-sloping trailing edge wings perform worse than the symmetric airfoil when $\alpha \leq 0^\circ$. Data also illustrate that it has a significant increase for the lift-to-drag ratios at small angles of attack ($0^\circ \sim \pm 3^\circ$). Moreover, the closer the angle of attack to 0° , the greater the increase. For example, for the cases of $+15^\circ$ upward-sloping and -15° downward-sloping trailing edges, the lift-to-drag ratios are more than 2 times that of the symmetrical airfoil at -3° and $+3^\circ$ angles of attack respectively, and more than 80 times that of the symmetrical airfoil at 0° angle of attack. In contrast, the increase of lift-to-drag ratios at big angles of attack ($\pm 6^\circ \sim \pm 10^\circ$) is less than those at small angles of attack. Also taking the cases of $+15^\circ$ upward-sloping and -15° downward-sloping trailing edges as the examples, the lift-to-drag ratios increase by 9% compared with the symmetrical airfoil at $\pm 10^\circ$ angles of attack, and by 33% at $\pm 6^\circ$. Focused on "Petrel-II" UG with rectangular airfoil, Xu et al [29] achieved the same conclusions as the present work through investigating different camber angles of the trailing edge at the angles of attack from -6° to $+6^\circ$. It shows that the camber trailing edge wings are particularly beneficial to improving the glide efficiency of the UGs at small angles of attack.

The pressure contours (Figs. 10 and 11) in the flow field surrounding the airfoil further confirm the advantages of the wing with variable camber trailing edge. On descending glide with a positive angle of attack, such as $+4^\circ$ (Fig. 10), there is a larger upward pressure difference between the lower and upper surfaces of the airfoil with downward-sloping trailing edge (Fig. 10(b)), which is conducive to raising lift of the glider. In the case of upward-sloping trailing edge (Fig. 10(a)), the opposite pressures at the leading edge and trailing edge reduce the lift and lift-to-drag ratio, thus resulting in a poor glide efficiency. By contrast, in the case of ascending glide with a negative angle of attack, such as -4° (Fig. 11), the similar trailing edge shape generates an opposite effect on the pressure difference in descending glide, as shown

in Fig. 10. That is to say, the upward-sloping trailing edge (Fig. 11(a)) contributes to the larger downward pressure difference between the upper and lower surfaces of the wing, thus increasing the lift, and the downward-sloping trailing edge facilitates the opposite pressures at the leading edge and trailing edge, thus decreasing the lift and lift-to-drag ratio in ascending glide (Fig. 11(b)).

(a) Upward-sloping

(b) Downward-sloping

Figure 10 Pressure contour in the flow field surrounding the airfoil with sloping angle of 15° at $+4^\circ$ angle of attack (unit: Pa)

(a) Upward-sloping

(b) Downward-sloping

Figure 11 Pressure contour in the flow field surrounding the airfoil with sloping angle of 15° at -4° angle of attack (unit: Pa)

In our investigation, for the sake of improving glide efficiency, the glider is recommended to glide at a large angle of attack, but it is not the larger the better. It is suggested that the angle of attack is less than 9° for the glider with symmetric airfoil, while for those with asymmetric airfoil, it is suggested to be less than 8° , according to the degree of asymmetry of the airfoil. The greater the asymmetry of the airfoil is, the smaller the max angles of attack can be. Generally, it is difficult to make the glider fly at a larger angle of attack. Thus, it is extremely important and efficient to equip the glider with a pair of variable camber trailing edge wings. The glider can get better glide efficiency through adjusting the sloping angle of the trailing edge according to the flight state, such as the downward-sloping trailing edge for descending and upward-sloping trailing edge for ascending glide. We have tried it using the developed lab-scale UG with flexible camber trailing edge wings, which will be described in Section 5.

4.4.2 Motion stability

The glider is generally expected to be statically stable, because its glide speed is very slow, normally less than 0.5 m/s. The viscous hydrodynamic moment coefficient T_z^α of the glider with symmetric airfoil is calculated to be negative from the CFD simulation. According to the stability criterion described in Section 3.3.1, it is deemed that the lab-scale UG with symmetric airfoil is statically stable.

From the achieved stability margins $G_{r\delta}$ of the lab-scale UG with variable camber trailing edge wings (Table 3), the lab-scale UG with flexible camber trailing edge wings is statically stable in both ascending glide with upward-sloping trailing edge wings (the upper left grey area in Table 3) and descending glide with downward-sloping trailing edge wings (the lower right grey area in Table 3). It shows that the suitable camber trailing edge does not affect the static stability of the glider. In literature [29], it has the same conclusion with “Petrel-II” UG with rectangular airfoil. When the trailing edge of the wings is bent down, the static stability of the glider can be maintained within the positive angles of attack. When the trailing edge is bent up, the glider can maintain static stability within the negative angles of attack.

Table 3 Stability margin $G_{r\delta}$ of the lab-scale UG with variable camber trailing edge wings

α (°)	Upward-sloping angles of the trailing edge (°)						Downward-sloping angles of the trailing edge (°)					
	30°	25°	20°	15°	10°	5°	-5°	-10°	-15°	-20°	-25°	-30°
-8	3.873	3.876	3.826	4.106	3.640	3.683	8.149	3.073	0.704	-11.312	-5.828	-7.209
-7	3.835	3.799	3.917	3.963	3.474	3.099	5.818	1.192	-2.706	-7.226	-3.310	-4.639
-6	3.790	4.254	4.388	4.589	3.913	4.323	4.780	2.338	-4.782	-4.558	7.596	5.935
-5	3.821	3.656	4.196	4.286	3.841	4.227	2.809	-4.144	-8.447	10.985	8.377	5.813
-4	4.157	4.355	4.957	5.728	5.123	2.843	-5.148	-2.274	-11.654	9.658	6.045	4.668
-3	4.333	4.721	5.601	6.846	5.214	5.839	-4.809	-0.709	13.717	7.674	5.094	4.396
-2	3.978	4.970	5.432	6.726	5.679	4.474	-1.545	4.536	13.152	7.524	5.068	4.321
-1	3.940	4.404	5.598	6.443	6.822	4.171	2.277	6.835	9.893	7.002	4.713	3.971
0	3.705	4.467	6.169	7.876	5.425	2.621	3.976	6.202	8.388	6.482	4.696	3.785
1	3.778	4.573	6.818	9.419	6.325	2.493	4.482	5.388	6.758	5.773	4.489	3.883
2	3.976	5.324	7.573	8.969	4.646	-0.527	3.968	5.587	6.663	5.353	4.429	3.547
3	3.852	5.280	8.050	6.156	1.133	-7.503	4.727	5.373	6.586	5.472	4.597	3.805
4	4.025	10.089	9.522	3.381	0.679	-4.674	3.276	4.749	5.469	4.712	4.201	3.537
5	4.699	8.871	11.598	-2.986	-2.778	1.475	3.181	3.332	3.917	3.860	3.558	3.229
6	4.552	8.099	-8.689	-7.824	-8.355	2.626	3.216	3.285	3.891	4.084	3.908	3.157
7	-3.232	-7.741	-10.554	-5.889	1.202	3.057	3.314	3.427	3.889	3.784	3.778	3.204
8	-6.124	-10.632	-14.900	5.224	2.305	8.133	3.625	3.811	4.418	3.988	3.895	3.290

Data in the lower left area (corresponding to the state of descending glide with upward-sloping trailing

edge) and upper right area (corresponding to the state of ascending glide with downward-sloping trailing edge) show that motions of the glider are unstable in some cases, such as in the green areas. The lift-to-drag ratios corresponding to those unstable gliding states are all less than 3 (Fig. 9). A better understanding can be obtained from the pressure contours in Fig. 10(a) and Fig. 11(b). The motion stages of the glider in Fig. 10(a) and Fig. 11(b) correspond to the ones in the lower left area and upper right area, respectively. From Figs. 10(a) and 11(b), the opposite pressure differences at the leading edge and trailing edge reduce the lift of the wings, and thus decrease the damping moment balancing the overturning moment. When the lift is too small to balance the overturning moment, the glider will lose its motion stability.

Also from Table 3, in the cases of unfavorable trailing edge shapes, i.e., with downward-sloping trailing edge wings on ascending glide and upward-sloping trailing edge wings on descending glide, the glider with bigger camber trailing edge wings, such as with the sloping angles of 25° and 30°, can still obtain good static stability within the general range of angle of attack $[-6^\circ, +6^\circ]$. That is to say, the glider with large camber trailing edge wings can still glide downward and upward even without changing the sloping direction of the trailing edge.

In order to validate the correctness of stability margin formula of Eq. (5) derived in the paper and the evaluation reliability according to Table 3, the dimensionless positional force arm $\overline{L}_\alpha$ of the glider under a small transient disturbance is calculated and applied to evaluate the static stability of the lab-scale UG with variable camber trailing edge wings. The dimensionless positional force arm $\overline{L}_\alpha$ is [39, 40, 42]

$$\overline{L}_\alpha = \frac{N(\alpha)}{L * Y(\alpha)} = \frac{T_z^\alpha}{C_Y^\alpha} \quad (6)$$

From Eq. (6) and Fig. 5, it is deemed that the smaller $\overline{L}_\alpha$ is, the more stable the vehicle is. When $\overline{L}_\alpha < 0$, the vehicle is statically stable.

Table 4 lists dimensionless positional force arm $\overline{L}_\alpha$ based on Eq. (6). It can be seen that the glider is statically stable in ascending glide with upward-sloping trailing edge wings (the upper left grey area in Table 4) and in descending glide with downward-sloping trailing edge wings (the lower right grey area in Table 4), which is consistent with the results in Table 3. In the lower left area and upper right area, some data labeled in green are also greater than zero. It illustrates that the glider is statically unstable under those flight conditions. The flight conditions corresponding to the data labeled in green in Table 4 are almost the same with those in Table 3. The rough consistence of the static stability results between Table

3 and Table 4 proves that the deduced formula Eq. (5) in this paper can be used to evaluate the motion stability of the glider. It is especially true for the glider with variable airfoil, since the computing cost can be greatly reduced using Eq. (5). Comparing data in grey areas with those in the column labeled in yellow (glider with symmetric airfoil), we can obtain that the glider with variable camber trailing edge wings has better static stability than that with symmetric airfoil.

Table 4 The dimensionless position force arm $\overline{L}_a$ of the glider with variable camber trailing edge wings

α (°)	Upward-sloping angles of the trailing edge (°)						Without sloping	Downward-sloping angles of the trailing edge (°)					
	30°	25°	20°	15°	10°	5°	0°	-5°	-10°	-15°	-20°	-25°	-30°
-8	-0.145	-0.142	-0.138	-0.132	-0.127	-0.112	-0.099	-0.082	-0.052	-0.007	0.096	0.288	0.738
-7	-0.150	-0.147	-0.142	-0.136	-0.130	-0.117	-0.101	-0.080	-0.033	0.030	0.203	0.856	-4.038
-6	-0.156	-0.152	-0.147	-0.141	-0.135	-0.118	-0.102	-0.075	-0.015	0.089	0.747	-1.903	-0.731
-5	-0.160	-0.157	-0.152	-0.146	-0.138	-0.123	-0.102	-0.070	0.029	0.285	-1.799	-0.552	-0.397
-4	-0.166	-0.162	-0.158	-0.151	-0.145	-0.125	-0.103	-0.058	0.204	0.930	-0.524	-0.363	-0.318
-3	-0.173	-0.170	-0.166	-0.158	-0.152	-0.132	-0.106	-0.038	1.881	-0.546	-0.336	-0.290	-0.272
-2	-0.181	-0.178	-0.175	-0.169	-0.163	-0.142	-0.107	0.028	-0.443	-0.308	-0.261	-0.247	-0.239
-1	-0.191	-0.190	-0.188	-0.184	-0.180	-0.166	-0.123	-1.163	-0.246	-0.231	-0.223	-0.220	-0.217
0	-0.205	-0.205	-0.207	-0.208	-0.210	-0.220	-0.506	-0.119	-0.195	-0.197	-0.198	-0.198	-0.199
1	-0.224	-0.227	-0.235	-0.245	-0.271	-0.624	-0.041	-0.138	-0.164	-0.174	-0.179	-0.183	-0.186
2	-0.248	-0.257	-0.278	-0.316	-0.450	0.190	-0.068	-0.122	-0.150	-0.160	-0.168	-0.171	-0.175
3	-0.277	-0.303	-0.343	-0.500	-7.772	0.016	-0.077	-0.117	-0.141	-0.151	-0.160	-0.164	-0.168
4	-0.324	-0.374	-0.505	-2.374	0.254	-0.027	-0.084	-0.114	-0.137	-0.145	-0.153	-0.157	-0.162
5	-0.409	-0.547	-1.238	0.456	0.206	-0.048	-0.087	-0.112	-0.131	-0.140	-0.148	-0.153	-0.156
6	-0.595	-1.239	1.238	0.160	0.014	-0.061	-0.090	-0.110	-0.128	-0.136	-0.143	-0.148	-0.152
7	-1.491	2.024	0.291	0.065	-0.016	-0.068	-0.091	-0.109	-0.125	-0.132	-0.139	-0.144	-0.147
8	0.948	0.380	0.136	0.020	-0.032	-0.072	-0.092	-0.107	-0.128	-0.128	-0.134	-0.139	-0.143

5 Tank experiments

Tank experiments were carried out by using the lab-scale UG with flexible camber trailing edge wings. Three airfoils were obtained by changing sloping angles of the trailing edge. The three airfoils are: NACA 0012 without deformed trailing edge, that with the upward sloping 15° trailing edge and that with the downward sloping 15° trailing edge.

The descending, ascending and pitch attitude of the lab-scale UG were controlled by a DC geared motor 25GA-370 driving three syringes to change the amount of water inside. The 6-DOF sensor JY-61 was used to measuring the triaxial accelerations and angular velocities in the body-fixed frame during the UG descending and ascending, and the SD card was used to recording data of the accelerations and

angular velocities of the glider. After the experiments, data in the SD card was read and performed integral calculation through the computer to obtain the velocities, trajectories and attitude angles of the UG. Figure 12 shows the lab-scale UG in descending and ascending glides in the tank.

(a) Descending glide

(b) Ascending glide

Figure 12 The lab-scale glider in the tank

Figure 13 illustrates the triaxial velocities of the glider in one glide profile obtained from the JY-61 sensor. Velocity of the glider was about 0.35 m/s. The lateral velocity v_z of the UG was less than 0.005 m/s which indicates the lab-scale UG has good yaw stability. It also can be seen that velocities in x-axis and y-axis were always changing during the descending and ascending. The reason is that the UG was constantly absorbing water and draining during the descending and ascending due to the shallow tank.

Figure 13 The triaxial velocities of the lab-scale UG in one glide profile

Then the lift-to-drag ratio (L/D) can be obtained according the following equation [38],

$$\frac{L}{D} = \frac{u}{w} \quad (7)$$

where u and w are the horizontal velocity and vertical velocity of the UG in the -fixed frame, respectively. Figure 14 illustrates the lift-to-drag ratios of the lab-scale UG with different trailing edge wings. From Fig. 14, the variation trend of the lift-to-drag ratio of the lab-scale UG with variable trailing edge wings is the

same as that achieved by the CFD simulation. At the negative angles of attack corresponding to the ascending glides, the lift-to-drag ratios of the glider with upward-sloping 15° trailing edge wings rise by 10%~35% compared with those of the glider with undeformed trailing edge wings. However, the lift-to-drag ratios of the glider with downward-sloping 15° trailing edge wings are lower. It illustrates that the downward-sloping trailing edge wings are unsuitable for ascending glide. On the contrary, at the positive angles of attack corresponding to the descending glide, the lift-to-drag ratios of the glider with upward-sloping 15° trailing edge wings are lower, which shows that the upward-sloping trailing edge wings are not suitable for descending glide. However, the lift-to-drag ratios of the glider with downward-sloping 15° trailing edge wings can increase by 20%~30% compared with those of the glider with undeformed trailing edge wings.

Comparing Fig. 14 with Fig. 9, it shows that the lift-to-drag ratios obtained from the CFD simulation are higher than those from the tank tests. The following two factors are considered to be responsible for the error. One is that the simplified ideal model in the CFD simulation makes drag of the glider lower than that of the physical glider in the tank tests. The other is that not the entire trailing edge is bent (Fig.3) and the open structure of the wing reduces the lift of the wing in tank tests.

Figure 14 Lift-to-drag ratios (L/D) obtained from the tank experiments

6 conclusions

A lab-scale underwater glider with flexible camber trailing edge wings was developed to investigate the effects of the variable trailing edge on flight performance of the glider. Changes of the attitude and

buoyancy of the lab-scale underwater glider can be achieved simultaneously through water suction and drainage, which helps greatly to reduce the size of the glider. The flexible wings can realize flexible camber change of the trailing edge through a flexible actuator: the steer-by-wire actuator.

Appropriate sloping direction of the trailing edge will improve lift-to-drag ratio of the UG greatly, especially at small angles of attack. When the glider flies at a positive angle of attack, the wings with downward-sloping trailing edge can provide a larger upward lift, thus increasing the lift-to-drag ratio and improving the glide efficiency on descending glide. However, the increase in lift-to-drag ratio is no longer noticeable when the angle of attack is greater than $+6^\circ$. On the contrary, when the glider flies at a negative angle of attack, the wings with upward-sloping trailing edge can provide a larger downward lift, thus increasing the lift-to-drag ratio and improving the glide efficiency in ascending glide. The larger the upward-sloping angle is, the larger the lift-to-drag ratio is. In the same way, the increase in lift-to-drag ratio is also no longer significant when the angle of attack is below -6° .

For the cases of variable trailing edge wings, the angles of attack corresponding to the minimum lift-to-drag ratios are away from 0° , i.e., the angles of attack are positive for the upward-sloping cases, and negative for the downward-sloping ones. Moreover, the larger the camber angle of the trailing edge, the larger absolute values of the angles of attack corresponding to the minimum lift-to-drag ratios. It is very beneficial for the UGs cruising at small angle of attack.

Similarly, appropriate sloping direction of the trailing edge is good for motion stability of the glider. The glider with upward-sloping trailing edge wings can obtain a good flight stability when gliding at a negative angle of attack in ascending glide, while the glider with downward-sloping trailing edge wings can obtain a good flight stability when gliding at a positive angle of attack in descending glide.

In the cases of adverse matching between the angles of attack and sloping directions of the trailing edge, viz. with upward-sloping trailing edge on descending glide and with downward-sloping trailing edge on ascending glide, the lift-to-drag ratios of the glider with variable camber trailing edge wings are lower than those of the glider with symmetric airfoil. However, the glider can obtain stability within a certain small angles of attack according to the sloping angles of the trailing edge. The lift-to-drag ratios corresponding to the state of motion instability are less than 3.

Tank experiments show that the lift-to-drag ratio of the lab-scale UG with appropriate variable camber trailing edge wings (i.e., with downward-sloping trailing edge on descending glide, and with upward-sloping trailing edge on ascending glide) can be increased by 10%-35% than that of the glider with symmetric airfoil. Moreover, results of the tank experiments prove the correctness and credibility of the

conclusions on the flight performance of the lab-scale UG with variable camber trailing edge wings obtained from the CFD analysis.

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Figures

Figure 1

Layout of the lab-scale underwater glider

(a) 3-D model

(b) Airfoil profile

Figure 2

Structure of the flexible wing with steer-by-wire actuator for deforming the trailing edge

Figure 3

Deformations of the trailing edge driven by steer-by-wire actuator

Figure 4

Change of the horizontal velocity with the net displacement volume at different glide path angles

Figure 5

The positional force/moment and rotational force/moment acting on the glider in vertical plane

(a) Symmetric airfoil

(b) Upward-sloping trailing edge

(c) Downward-sloping trailing edge

Figure 6

Diagram of the airfoils with different trailing edges

Figure 7

Numerical modeling of the glider

(a) The computational domain and boundary conditions

(b) Grids around the airfoil

Figure 8

Numerical modeling of the airfoil

(a) Upward-sloping trailing edge

(b) Downward-sloping trailing edge

Figure 9

Lift-to-drag ratios (L/D) of the glider with variable camber trailing edge wings at different angles of attack

□

(a) Upward-sloping

(b) Downward-sloping

Figure 10

Pressure contour in the flow field surrounding the airfoil with sloping angle of 15° at $+4^\circ$ angle of attack (unit: Pa)

(a) Upward-sloping

(b) Downward-sloping

Figure 11

Pressure contour in the flow field surrounding the airfoil with sloping angle of 15° at -4° angle of attack (unit: Pa)

(a) Descending glide

(b) Ascending glide

Figure 12

The lab-scale glider in the tank

Figure 13

The triaxial velocities of the lab-scale UG in one glide profile

Figure 14

Lift-to-drag ratios (L/D) obtained from the tank experiments