Analysis of Store Separation from Weapon Bay of a Blended-Wing-Body Underwater Glider

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***Abstract*—Based on the kinetic equation and kinematic equation, trajectories of a new blended-wing-body(BWB) underwater glider are simulated with a changing deflection of the center of gravity (CG), which indicates that the glide ratio degrades with the deflection of the center of gravity going larger. Numerical study on the store separation from the weapon bay of a BWB underwater glider, supported by the computational fluid mechanics and the six-degree-of-freedom model, is carried out. The specified separating course and the flow structure of the weapon bay are demonstrated. With the calculated hydrodynamic forces, the kinetic equation and kinematic equation are solved to get the affected trajectories of different attack angles.**

I. INTRODUCTION

Underwater glider with the properties of high range, endurance, and low costs, was first proposed by Stommel (Stommel, et al. 1989). It's controlled by changing the buoyancy and the position of movable mass to keep diving, ascending states and the pitching, attacking angles. Thus, gliders could travel with little noise and consume less power (Seo et al., 2008). Some research teams have developed this kind of unmanned underwater vehicle (UUV), such as the Slocum (Webb et al., 2001), the Seaglider (Eriksen et al., 2001), which were component with a cylinder-shaped body and a pair of fixed wings. And the hydrodynamic performance is studied (CHEN Ya-jun et al., 2015). A new kind of glider named blended-wing-body underwater glider was proposed recently, such as the ZRAY (Hussain et al., 2011). This new kind of underwater glider is better at reducing interface drag and shows excellent hydrodynamic performance. As for the store separation, most loads are set as part of the main cylinder body, which separates by gravity on the head with or without a thrust (SONG Bao-wei et al., 2009). Other methods are launching on top of the UUV or by the torpedo tube. The internal store releasing was studied by researchers based on the aerodynamics. Most papers focused on the store or the cavity flow (K.M. Nair et al., 2017).

This paper focus on the effects on the BWB underwater glider. One method for simulation of store separation in the presence of unsteady flow involves the use of time accurate Computation Fluid Dynamic (CFD) analysis coupled with 6-DOF simulation (Kevin Roughen et al., 2009, Freeman et al., 2006, Murman et al., 2004). The trajectory simulation of the initial glider without store is carried out with the commercial software MATLAB, and the 6-DOF module of the commercial software FLUENT and the dynamic mesh technology are utilized to solve the store separation process.

II. COMPUTATIONAL METHOD

A. Kinetic and Kinematic Equations

To get the steady trajectory of the initial BWB underwater glider, a simplified model of 2D is applied. Based on the theory of momentum and moment of momentum, the kinetic equation is shown below:

$$A_{m\lambda 1} \cdot \dot{V} = -A_{vw} A_{m\lambda 2} \cdot V + A_{FM} \qquad (1)$$

$$A_{m\lambda 1} = \begin{bmatrix} m+\lambda_{11} & 0 & -m \cdot y_c \\ 0 & m+\lambda_{22} & m \cdot x_c + \lambda_{26} \\ -m \cdot y_c & m \cdot x_c + \lambda_{26} & J_{zz} + \lambda_{66} \end{bmatrix}$$

$$V=\begin{bmatrix} v_x \\ v_y \\ w_z \end{bmatrix}, \qquad A_{vw}=\begin{bmatrix} w_z & 0 & 0 \\ 0 & w_z & 0 \\ 0 & 0 & w_z \end{bmatrix}$$

$$A_{m\lambda 2}=\begin{bmatrix} 0 & -m & -m\cdot x_c \\ m & 0 & -m\cdot y_c \\ -m\cdot x_c & m\cdot y_c & 0 \end{bmatrix}$$

And m means the mass of the glider, λ marks for the added mass, the coordinate of center of gravity is (x_c, y_c), A_{FM} is the forces and moments including hydrodynamic forces and the buoyancy forces.

As for the kinematic equation, the description of the relationship between the center of gravity and its velocity is shown with the attitude angles.

$$\left\{\begin{array}{c} v=\sqrt{v_x^2+v_y^2} \\ v_x=v\cos\alpha; v_y=-v\sin\alpha \\ \alpha=\tan^{-1}\left(v_y/v_x\right) \\ \dot{\theta}=\omega_z \\ x_0=v_x\cos\theta-v_y\sin\theta \\ y_0=v_x\sin\theta+v_y\cos\theta \\ \sin\Theta=\sin\theta\cos\alpha-\cos\theta\sin\alpha \end{array}\right\} \tag{2}$$

Pitching angle θ, trajectory inclination angle Θ. Attack angle is marked by α, and the center of buoyant is (x_o, y_o).

B. Governing Equations

Numerical simulation of the store separation is performed with solving the unsteady RANS equations, which decomposes the variables of the instantaneous N-S equations into the mean values and the fluctuating values. The fluid material is water, which means an unsteady, incompressible viscid fluid, therefore, the governing equations can be described as:

$$\frac{\partial u_i}{\partial x_i}=0 \tag{3}$$

$$\frac{\partial(\rho u_i)}{\partial t}+\frac{\partial(\rho u_i u_j)}{\partial x_j}+\frac{\partial}{\partial x_j}\left(\rho\overline{u_i' u_j'}\right)=-\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}\mu\frac{\partial u_l}{\partial x_l}\delta_{ij}\right]+\rho f_i \tag{4}$$

And $u_i, u_j\ (i,j=1,2,3)$ are the velocity components, μ is the dynamic viscosity coefficient of water, f_i is the mass force, and $\rho\overline{u_i' u_j'}$ is the Reynolds stress term, δ_{ij} is the Kronecker delta function.

C. Geometry Model and CFD Grids

Shape design of the BWB underwater glider has been studied. Since this paper focuses on the store separation, a typical symmetrical airfoil NACA 0012 is used as a baseline airfoil for the main body while NACA0010 for the wings, according to Sun's research (Sun, C. et al., 2017). And the geometry model is shown in figure 1. The model parameters chosen in this paper are described in table 1. Where m_h means the fixed mass distributed throughout the body, m_b is the variable mass that changes with the diving or ascending state, and $\overline{m}$ is the controlled mass. Other constant coefficients are not shown below.

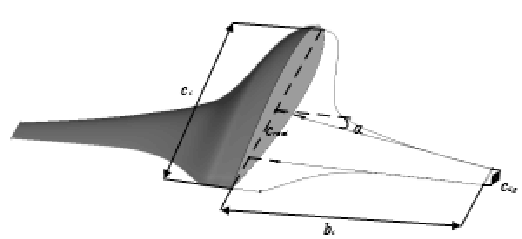


Fig. 1. Geometry model of the glider

TABLE 1. Model parameters

Parameter	$\alpha(^\circ)$	$c_t(m)$	$c_{root}(m)$	$b_t(m)$
Value	10.65	3	0.9	3.5
Parameter	c_{tip}(m)	$\overline{m}(kg)$	$m_h(kg)$	$m_b(kg)$
Value	0.3	170	1130	30

The section of the cabin and object are shown Figure 2. The object is a cylinder body of 0.324m diameter and 1.5m length. While the cabin's average length is 1.766m, and width 0.5m, the top of the cabin is cambered, the lengthwise section is trapezoidal. The inclination angle theta is 10º, and the cabin located at the wing to body part. As for the object, it is installed with an opposite direction to the glider.

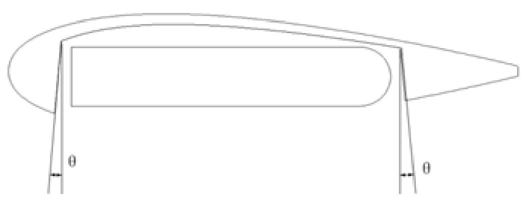
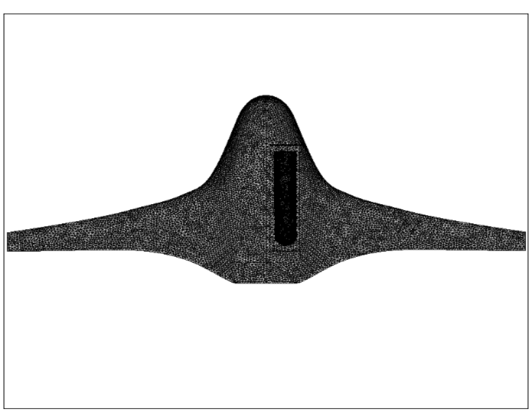


Fig. 2. Vertical section of cabin and object

Dynamic and unstructured mesh method is applied in this paper, which is validated to be enough accurate in engineering by some aerodynamics researchers (L. Formaggia, et al., 1988). With store falling from the bay, there must be large deformations to the mesh; To make sure of the accuracy, a better method is applying the unstructured mesh and the built-in 6DOF module with a user defined function (UDF) to the calculating procession. The unstructured meshes of the UUV and the bay are shown in figure 3.



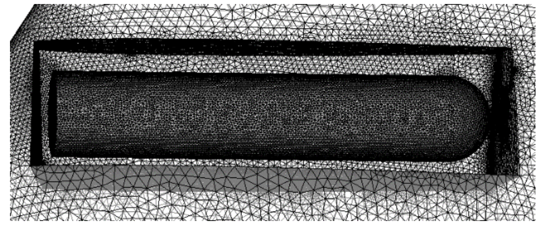


Fig. 3. Mesh for the glider and object.

III. RESULTS AND DISCUSSION

With different offsets of the center of gravity, the glider goes in a variable of routines. Though the simulation module, the trajectories of the glider are shown in figure 4.

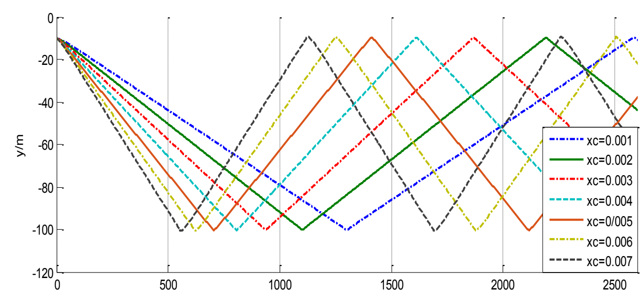


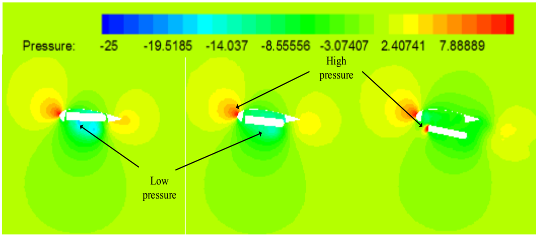
Fig. 4. trajectories with different CG offsets

Obviously, the glide ratio degrades with the axial CG offset going bigger, which means the gliding distance in a single journey declines. Moreover, the velocity of the course increases. And the initial steady states for different angle of attack at the axial CG offset of 0.001 are shown in table 2.

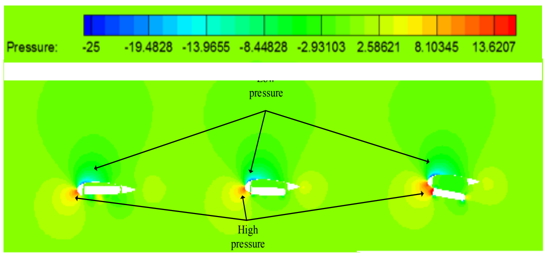
TABLE 2. Steady trajectory parameters

Attack angle α (degree)	Velocity v(m/s)	Pitching angle θ(degree)
2	0.514	-2.251
4	0.287	-1.161
6	0.235	-3.332
8	0.203	-5.265
-2	0.514	2.251
-4	0.287	1.161
-6	0.235	3.332
-8	0.203	5.265

The velocity decreases as the angle of attack increases while the pitching angle tends to be increasing, which gives an indication that the glider may move faster vertically but slower in the horizontal direction.



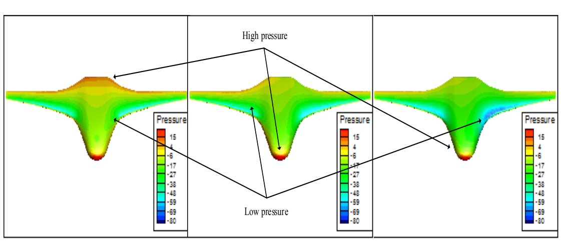
(a) Ascending course with the attack angle of -8º.



(b) Diving course with the attack angle of 8º.

Fig. 5. Vertical slices of pressure contours around the cabin and object.

Store's existence affects the fluid structure whether the glider is diving or ascending. The low pressure area spreads downstream while it fades under the UUV along with the store's falling when the glider is ascending shown in figure 5(a). Moreover, when the store-falling goes with the glider's diving, there will be a high pressure area spreading forward and form a continuous pressure transition region in the cabin as shown in figure 5(b). Pressure contours on the glider's surfaces are shown in figure 6, which we take the diving course at an attack angle of 4º for example. It's obvious that the pressure decreases at the top surface but increases on the cabin surfaces and when part the object falling out of the cabin, pressure around the cabin decreases immediately. There is the same changing tendency when the glider is ascending but with higher pressure on lower surface.



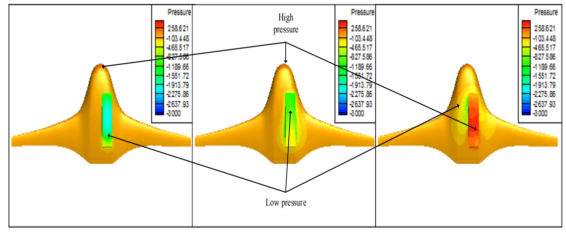
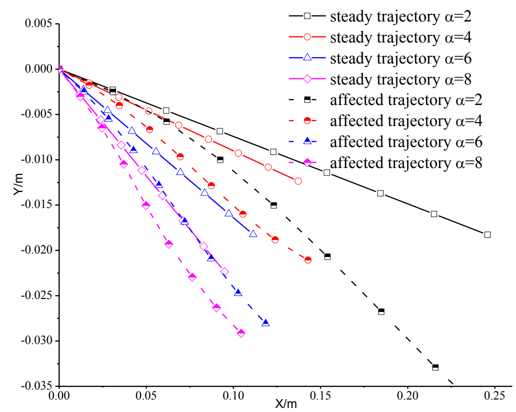
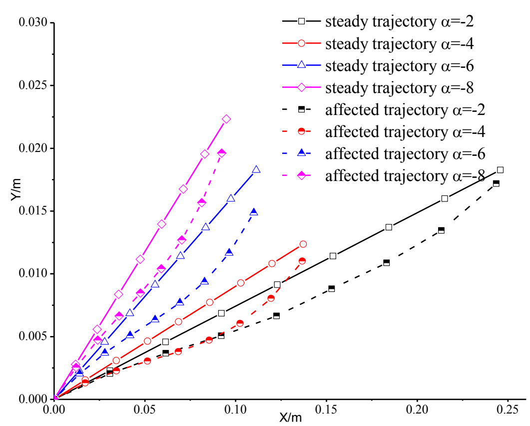


Fig.6. Top and bottom view of surface pressure contours of the glider.

According to the hydrodynamic forces and moments, the kinetic and kinematic equations can be solved with the fourth order Runge-Kutta method. A cooperation of the steady and affected trajectories are shown in the figure7, with different angle of attack.



(a) Diving vertical trajectories.

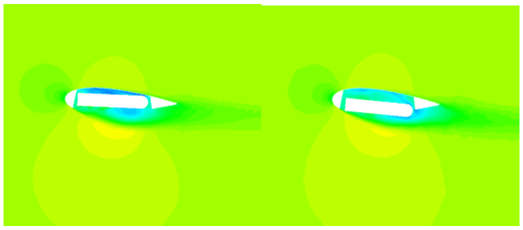


(b) Ascending vertical trajectories.

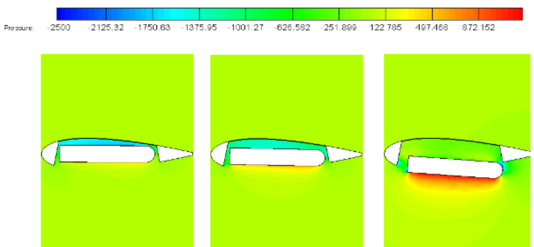
Fig. 7. Steady and affected trajectories.

The glider goes a steeper diving trajectory, but the glider slows down first, then speeds up to ascend during the ascending course as a result of store separation, which means the vertical component of diving and ascending velocity increasing with the store separation process.

To get a detail view of the weapon bay flow structure and the effects on the underwater glider, simulations of the steady flow structure are promoted. Here takes the ascending course at the attack angle of 8-degree for example in figure 8.



(a) Velocity contours with the store separation.



(b) Pressure contours with the store separation

Fig. 8. Weapon bay flow structures with store separation.

Shown in the figure 8(a), the weapon bay flow structure is classified into an open shear flow, and the separation of the store expands the shear layer till the store out of the weapon bay. Once the shear layer is broken, the pressure in the weapon bay increases as shown in the figure 8(b), which results in a slope ascending journey.

IV. CONCLUSION

Solving the kinetic and kinematic equations with changing offsets of the CG, the glide ratio degrades when the offsets increase, which means we could design a less catabiotic glider with a tiny deflection of CG. However, this may result in a tardy travel.

The weapon structure, limited by the whole glider model, lead to an open shear flow structure. And the store separation expands the shear layer, which could delay the broken of the shear layer. Thus, the affected trajectories show a stable state, then become steeper. And the bigger the attack angle, the steep turning point shows earlier.

To ensure a safe store separation, the ascending course seems to be much more outstanding one than the diving course. Moreover, the separation goes easier with a bigger attack angle of the ascending course.

REFERENCES

[1] Stommel, H. The Slocum Mission. J. Oceanography, 1989, 2(1): 22-25

[2] Seo, D.C., Gyungnam, J., Choi, H.S. Pitching control simulation of an underwater glider using CFD analysis. In: Proceedings of the OCEANS'08 MTS/IEEE Kobe Techno-Ocean, 2008.

[3] Webb, D.C., Simonetti, P.J., Jones, C.P. Slocum: an underwater glider propelled by environmental energy. IEEE J. Oceanic Eng. 2001, 26 (4), 447-452.

[4] Eriksen, C.C., Osse, T.J., Light, R.D., Wen, T., Lehman, T.W., Sabin, P.L., Ballard, J.W., Chiodi, A.M. Seaglider: a long range autonomous underwater vehicle for oceanographic research. IEEE J. Oceanic Eng. 2001, 26 (4), 424–436

[5] CHEN Ya-jun, CHEN Hong-xun, MA Zheng. Hydrodynamic analyses of typical underwater gliders. Journal of Hydrodynamics, Ser. B, 2015, 27(4):556-561.

[6] Hussain, N.A.A., Arshad, M.R., Mohd Mokhtar, R. Underwater glider modelling and analysis for net buoyancy, depth and pitch angle control. Ocean Eng. 2011,38 (16), 1782-1791.

[7] SONG Bao-wei, ZHAOE, LI Jia-wang. Method and safety of load separation of AUV. Computer Simulation, 2009, 26(1), 174-177(in Chinese).

[8] K.M. Nair, S. Sarkar, Z. Labana. Self-sustained oscillation for a three dimensional transonic cavity using LES. Fluid Mechanics and Fluid Power-Contemporary Research. Springer India, 2017

[9] Kevin Roughen, Xiaojian Wang, Oddvar Bendiksen, "A System for Simulation of Store Separation Including Unsteady Effects," 47th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition 5 - 8 January 2009, Orlando, Florida.

[10] Freeman, J. A., "Applied Computational Fluid Dynamics for Aircraft-Store Design, Analysis and Compatibility," 44th AIAA Aerospace Sciences Meeting and Exhibit, AIAA 2006-456, 9 - 12 January 2006, Reno, Nevada.

[11] Murman, S. M., Aflosmis, M. J. and Berger, M. J., "Simulations of Store Separation from an F/A-18 with a Cartesian Method," Journal of Aircraft. Vol. 41, no. 4, pp. 870-878. July-Aug. 2004.

[12] Sun, C., Song, B., Wang, P. Parametric geometric model and shape optimization of an underwater glider with blended-wing-body. Int. J. Nav. Archit. Ocean Eng. 2015, 7 (6), 995-1006.

[13] L. Formaggia, J. Peraire and K. Morgon, "Simulation of a store separation using the finite element method," Appl. Math. Modelling, 1988, Vol. 12.