Modelling hydrodynamic characteristics of the underwater glider based on Computational Fluid Dynamics

K Stryczniewicz¹, W Stryczniewicz² and R Szczepaniak³

¹ Warsaw University of Technology, Department of Aerodynamics, Institute of Aeronautics and Applied Mechanics, Nowowiejska 24, 00-665 Warsaw, Poland
² Łukasiewicz Research Network - Institute of Aviation, Department of Aerodynamics, Al. Krakowska 110/114, 02-256 Warsaw, Poland
³ Polish Air Force University, Dywizjonu 303 35, 08-521, Dęblin, Poland

kamila.stryczniewicz@meil.pw.edu.pl

Abstract. The underwater glider is buoyancy-propelled Autonomous Underwater Vehicle (AUV). Their propulsion relies upon changing their buoyancy with internal pumping systems enabling them upward and downward motion. In the presented paper, the forward gliding motions are generated by hydrodynamic lift forces exerted on a pair of hydroplanes attached to a glider hull. The hydrodynamic characteristics of a glider were determined using Computational Fluid Dynamics (CFD). A 3D model was created for the simulation of flow behaviour in the Baltic Sea. The lift and drag forces distribution at different angles of attack was studied for Reynolds number 10⁵. The flow velocity was 0.5 m·s⁻¹ and the angle of the attack varied from −30° to 30° in steps of 2°. Results from the CFD constitute the basis for the calculation the equations of motions of the glider in 6 degrees of freedom. The vehicle motion simulation will be achieved through numeric integration of the equations of motion. This work will contribute to dynamic modelling and three-dimensional motion simulation of the torpedo-shaped underwater glider.

1. Introduction

The inspiration to this work has come from intensive research in the field of modelling the dynamics of underwater vehicles, their manoeuvrability and performance, driven by their increasing applications in oceanography, military, natural environment safety. The research objective is to study the general dynamics model of an underwater vehicle with the aid of methods of the CFD for accurate assessment of dynamic effects between the vehicle and the external seawater environment. The vehicles are inertia propelled, i.e. move due to mass or configuration of mass change, or hybrid propelled, i.e. using inertia and engines to move. The steady-state gliding motion is defined by Zhang et al., 2012, as: “a particular change in buoyancy and fixed position of moving mass, the state variables of the glider remain unchanged and angular velocity remains zero for its sawtooth gliding motion”.

The paper focuses on inertia-based propelled AUV, i.e. not equipped with thrusters. AUVs constitute, then, a class of underwater vehicles not equipped with external propulsion systems. There are numerous types of such AUV currently available, such as Slocum [1], Spray [2] or Sea-glider [3]. They are designed for long-range missions, even 9 months on a single mission, consume small energy, are cost-efficient and exhibit significant endurance. They are applied in oceanography, in rescue and cleaning sea missions. Their propulsion relies upon changing the buoyancy with internal pumping...
systems enabling them upward and downward motions, and their forward gliding motions are generated by the hydrodynamic lift forces exerted on a pair of wings attached to a glider hull. The resulting AUV motion is a “saw-tooth motion” pattern in the vertical plane and a straight line motion in the horizontal plane. Low energy and easy propulsion have enabled for the involvement of various AUV in real applications, where either a single glider or a group [4, 5]. Another propulsion method for AUV is by using a movable internal mass [6, 7]. Other kind of motion of an AUV described in literature is along a spiral [8]. The spiral motion can be obtained by rotating an internal mass, e.g., the battery pack, or a rudder attached to the tail section of the glider.

2. Methods
An adequate model of hydrodynamic interactions is utterly important for a mathematical description of an AUV dynamics. In the late 1960s, Gertler and Hagen [9] proposed a fully analytical yet quite complex set of formulas for hydrodynamic force and moment components in the body-fixed reference frame, which are reminiscent of flight dynamics. Most recently, the CFD methods have become increasingly popular in hydromechanical modelling of AUVs. RANS-based simulations have been used to help calibrate the coefficient-based models [10, 11] or to provide steady-state hydrodynamic characteristics for such models [12-14]. Different turbulence models applied to RANS simulations of flows past a drifting submarine have been investigated and compared [15]. In a similar work [16], the RANS simulations have been used to calculate flow and forces past a submarine performing steady turns.

One of the most advanced applications of the CFD method consists in solving the full set of equations for unsteady turbulent flow (URANS model) simultaneously, i.e. fully-coupled with the equations of motion. It means that either the flow equations need to be solved in a domain which changes in time in a priori unknown way or the flow problem needs to be posed and solved in the body-fixed non-inertial reference frame. In the latter case, the far-field conditions become time-dependent and non-uniform. Yet another approach to the CFD-based determination of the hydrodynamic loads is presented in the study by Xiaocui et al. [17]. In this work, the computational domain is divided into two parts: the internal part surrounding the submarine and the “far-field” part around. Each part has been meshed independently. The entire domain moves linearly at an instantaneous velocity of the submarine but only the internal mesh performs rotary motion following the spatial orientation of the vehicle. This way, the problem of deforming meshes is replaced with the interpolation problem at the interface of sliding meshes. The accuracy of force prediction is exceptionally high. In this study Commercial CFD solver ANSYS Fluent 18.2 has been used to solve the steady-state Reynolds averaged Navier Stokes (RANS) equations. The Shear Stress Transport (SST) k – ω model was chosen for the turbulence model, which is widely used in flow separation problems and likely to be found at the aft of the AUV.

2.1. Geometry
The geometry of the AUV was created in SolidWorks 2018, commercial CAD software, and was designed based on the gliders commonly known in the literature. Our glider has a torpedo-shaped hull with tail shapes and fixed hydroplanes at the rear part. Torpedo-type hull is a cylindrical body with a large ratio between the length and diameter, L/D = 8. This shape provides good properties and is widely used by all major manufacturers of AUVs. The vehicle presented in figure 1 is symmetrical along the XZ and XY planes, for this reason, the calculations were performed for the half of the body to save the calculation costs.

![Figure 1](image_url). The studied geometry.
To model the profiles of the bow and stern of the vehicle, *Myring Equations* are commonly used. These theoretical equations describe curves for bow and stern of torpedo bodies generating the smallest possible drag coefficient [21]. The equations are as follows:

- **Bow,**
  \[ r_1(x) = \frac{1}{2}D \left[ 1 - \left( \frac{x-a}{a} \right)^2 \right]^{\frac{1}{n}} \]  

- **Stern,**
  \[ r_2(x) = \frac{1}{2}D - \left[ \frac{3D}{2c^2} - \frac{tg\theta}{c} \right] (x - a - b)^2 + \left[ \frac{D}{c^3} - \frac{tg\theta}{c^2} \right] (x - a - b)^3 \]

where all parameters of the equations are geometric (except for parameter \( n \)) and are shown in figure 2. These equations are used with the purpose of validation the studied geometry according to the optimal hydrodynamic shape.

**Figure 2.** Schematic figure of the AUV hull and geometric parameters of Myring Equations [21].

**Table 1.** Formatting sections, subsections and subsubsections.

| Parameter | Dimension, m |
|-----------|--------------|
| a         | 0.31         |
| b         | 1.1          |
| c         | 0.6          |
| D         | 0.25         |

**Figure 3.** Bow profiles analyzed for different values of parameter \( n \).
Myring equations show that the bow of the studied glider is well-fitted if \( n=2 \). A higher length-to-diameter ratio (L/D) is desirable for a glider. The predicted value of \( L / D = 8 \) is sufficient.

### 2.2. CFD Analysis

The glider under analysis is assigned for the Baltic Sea mission; therefore, the maximum operational depth is 25 m, where the absolute pressure is around 3500 hPa. According to the [22], the density of the water in the Baltic Sea at the 10°C is \( \rho=1005 \text{ kg·m}^{-3} \) and the dynamic viscosity is \( \mu=1.33\times10^{-3} \text{ kg·m}^{-1}·\text{s}^{-1} \). The kinematic viscosity was specified at \( \nu=1.3\times10^{-6} \text{ m}^2·\text{s}^{-1} \).

ITTC [21] recommendations for marine CFD applications to specify that the computational domain around the experimental glider, shown in figure 5, should extend \( L_a (1-2 \text{ L}) \) in the upstream of the leading edge of the body \( (L_h = 1.3 \text{ L}) \) in the radial direction (from the centreline of the body) and \( L_f=3-5 \text{ L} \) in the downstream of the trailing edge of the body. These dimensions of the external domain were examined.
Figure 6. Distribution of the cell around the 3D model of the underwater glider.

The inner domain (cylinder shape) around the body was discretized with the unstructured mesh. The outer domain was the structured mesh. Mesh interface between the two domains was established. The volume tetra mesh was created with the Robust (Octree) method. The mesh should be dense in areas where the flow velocities are sensitive to grid spacing and coarse in other areas. Due to that reason the region around the hull was concentrated. 10 prism layers proved enough to perform flow characteristics in the boundary layer, figure 6. The thickness of the boundary layer was set according to the ITTC, CFD marine recommendation [19]:

$$\delta = 0.035 L \cdot Re^{-\frac{1}{7}}$$  \hspace{1cm} (3)

where: L – the length of the glider [m], Re – Reynold number = \(\frac{v \cdot L}{\nu}\), (v - velocity of the glider [m·s\(^{-1}\)]; \(\nu\) – kinematic viscosity [m\(^2\)·s\(^{-1}\)]). Relying on [19], the non-dimensional wall distance can be defined in terms of Reynolds number in the following way:

$$\frac{y}{L_{pp}} = \frac{y^+}{Re \sqrt{C_f}}$$  \hspace{1cm} (4)

where: y is the first required cell height and \(C_f\) is an estimate of the skin friction coefficient, based on the ITTC standard method.

$$C_f = \frac{0.075}{(\log_{10} Re - 2)^2}$$  \hspace{1cm} (5)
Table 2. Flow parameters.

| Parameter | Dimension, m |
|-----------|--------------|
| $V$, ms$^{-1}$ | 0.5          |
| $Re$      | $7.7\times10^5$ |
| $C_f$     | 0.004966     |

The values of wall distance parameter distribution are presented in figure 7.

![Wall distance parameter distribution](image)

Figure 7. Wall distance parameter distribution.

Commercial CFD solver ANSYS Fluent 18.2 was used to solve the steady-state Reynolds averaged Navier Stokes (RANS) equations. The Shear Stress Transport (SST) $k$ – $\omega$ model is chosen for the turbulence model, which is widely used in flow separation problems and likely to be found at the aft of the AUV. The convergence is decided by the standard deviation of the viscous pressure resistance coefficient and frictional resistance coefficient displayed in per cent of the average force. The convergence criterion in the present study is set as 1% for the viscous pressure resistance coefficient and frictional resistance coefficient. Computations are carried out until the steady state is reached [20]. The glider was tested for the constant velocity 0.5 m·s$^{-1}$ and range of pitch angle ($\alpha = -30^\circ$ to $30^\circ$ in steps of $2^\circ$), the drag and lift coefficients are computed for the front reference surface.
Figure 8. Drag coefficient as a function of pitch angle $\alpha$.

Figure 9. Lift coefficient (Cl) as a function of pitch angle $\alpha$. 

Figure 10. Velocity magnitude around the glider body: $V=0.5 \text{ m} \cdot \text{s}^{-1}$, pitch angle from $5^\circ$ to $30^\circ$. X0Z geometry plane.

Figure 11. Absolute pressure around the glider body: $V=0.5 \text{ m} \cdot \text{s}^{-1}$, pitch angle from $5^\circ$ to $30^\circ$. X0Z geometry plane.
3. Conclusions
In this paper, the hydrodynamic single-phase flow around the underwater glider was discussed. The study was related to seawater flow in the turbulent regime by using the ANSYS Fluent R18.2 commercial software. The results show the proper tendency in the hydrodynamic characteristic as a function of pitch angle $\alpha$. Furthermore, the results were compared with the results presented in the literature [18]. The other force, such as added mass, needs to be considered in the future. The results from the CFD constitute the basis for the calculation of equations of motions of the glider in 6 degrees of freedom. Therefore, vehicle motion simulation will be achieved through numeric integration of the equations of motion. The equations of motion are formulated as Ordinary Differential Equations. The ODE problem will be solved by Runge-Kutta 4th order method in MatLab. This work will contribute to dynamic modelling and three-dimensional motion simulation of a torpedo-shaped underwater glider.

4. References
[1] Webb D C, Simonetti P J and Jones C P SLOCUM, an underwater glider propelled by environmental energy 2001 IEEE J. Oceanic Eng. 26 447–52
[2] Sherman J, Davis R E, Owens W B and Valdes J The autonomous underwater glider ‘‘spray’’ 2001 IEEE J. Oceanic Eng. 26 437–46
[3] Eriksen C C, Osse T J, Light R D, Wen T, Lehman T W, Sabin P L, Ballard J W and Chiodi A M 2001 Sea-glider: a long range autonomous underwater vehicle for oceanographic research IEEE J. Oceanic Eng. 26, 424–36
[4] Zhang F, Fratantoni D M, Paley D, Lund J and Leonard N E Control of coordinated patterns for ocean sampling 2001 Int. J. Control 80 1186–99
[5] Leonard N E, Paley D A, Davis R E, Fratantoni D M, Lekien F and Zhang F Coordinated control of an underwater glider fleet in an adaptive ocean sampling field experiment in Monterey bay 2001 J. Field Robot. 27 718–40
[6] Graver J, Leonard N E Underwater glider dynamics and control. In: 12th International Symposium on Unmanned Untethered Submersible Technology, Durham, 2001, 1–14.
[7] Bhatta P Leonard N E Nonlinear gliding stability and control for vehicles with hydrodynamic forcing 2008 Automatica 44 1240–50.
[8] Zhang S, Yu J, Zhang A and Zhang F Spiraling motion of underwater gliders: Modeling, analysis, and experimental results 2013 Ocean Engineering 60 1–13
[9] Gertler M, Hagen G R Standard equations of motion for submarine simulation Report 2510 Naval Ship Research and Development Center, June 1967.
[10] Su Y, Zhao J, Cao J and Zhang G Dynamics modeling and simulation of autonomous underwater vehicles with appendages 2013 J. Marine Sci. Appl. 12 45-51.
[11] de Barros E A, Pascoal A, de Sa E Investigation of a method for predicting AUV derivatives 2008 Ocean Engineering 35, 1627–36.
[12] Isa K, Arshad M R and Ishak S A hybrid-driven underwater glider model, hydrodynamics estimation, and an analysis of the motion control 2014 Ocean Engineering 81, 111-29.
[13] Liu F, Wang Y, Niu W, Ma Z and Liu Y Hydrodynamic performance analysis and experiments of a hybrid underwater glider with different layout of wings 2014 IEEE, 978-1-4799-3646-5/14
[14] Singh Y, Bhattacharyya S K and Idichandy V G CFD approach to steady-state analysis of an underwater glider 2014 IEEE, 978-1-4799-4918-2/14
[15] Phillips A B, Turnock S R and Furlong M Influence of turbulence closure models on the vortical flow field around a submarine body undergoing steady drift 2010 J. Marine Sci. Techn. 15 201-17
[16] Zhang J T Jordan A M, Gerber A G, Gordon A, Holloway L and Watt G D Simulation of the flow over axisymmetric submarine hulls in steady turning 2013 Ocean Engineering 57 180–196
[17] Xiaocui W, Yiwei W, Chenguang H, Zhiqiang H and Ruiwen Y An effective CFD approach for marine-vehicle maneuvering simulation based on the hybrid reference frames method 2015 Ocean Engineering 109 83–92
[18] Singh Y, Bhattacharyya S K, Idichandy V G CFD approach to modelling, hydrodynamic analysis and motion characteristics of a laboratory underwater glider with experimental results 2017 J. Ocean Eng Sci 2 90–119
[19] ITTC, Recommended procedures and guidelines: practical guidelines for ship CFD applications, 7.5, ITTC, 2011, pp. 1–18.
[20] Ichihashi N, Ikebuchi T and Arima M Proc. 18th ISOPE conf 2008 Canada 156–61. ISBN: 1-880653-68-0
[21] Myring D F A Theoretical Study of Body Drag in Subcritical Axisymmetric Flow 1976 AEQ 27 186-94
[22] Lepparanta M and Myrberg K 2009 Physical oceanography of the Baltic Sea (Chichester UK Praxis Publishing Ltd) ISBN 978-3-540-79702-9