Experimental analysis on hydrodynamic coefficients of an underwater glider with spherical nose for dynamic modeling and motion simulation

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Abstract

In this paper, we present a study of an underwater glider with a cylindrical body, a conical end shape and a spherical nose with NACA0009 airfoil wings. In the experimental section, we investigate the hydrodynamic coefficients of drag and lift as well as the torque on the glider then analyze the launch velocity, launch angles, angular velocity, and displacement range as the main parameters for evaluating of motion dynamics. In the numerical section, we investigate the optimal performance of the glider using the meta-heuristic optimization method in order to find the path and range of motion of the moving mass and control of the sea glider, which is very important for navigation scope. To be specific, body and wings hydrodynamic coefficients are obtained in the velocity range of $[0.2, 1] \text{ m/s}$; According to the results, the drag coefficient increases with increasing velocity, while the lift coefficient increases up to velocity of 0.8 m/s , then decreases at velocity of 1 m/s . Also, the wing drag coefficient decreases with increasing velocity, while the wing lift coefficient increases with increasing velocity. In the next step, in order to calculate an optimum ratio between obtained depth and horizontal distance, the designed algorithm investigate the glider launch angle and finally, the 10 degrees launch angle is chosen as the optimum angle. Subsequently, the analysis performed on mass center displacement range shows that the oscillation interval $[-0.045, 0.085] \text{ m}$ is an optimum displacement domain.

Keywords Underwater glider · Towing tank · Hydrodynamic coefficients · Motion dynamics modeling · Meta-heuristic algorithm

Abbreviations

A_{body}	Body cross section area (m^2)	I_B	Glider moment of inertia matrix (kg m^2)
A_{wing}	Wing cross area in top view (m^2)	I_{xx}	Glider moment of inertia about the x axis (kg m^2)
B	Buoyancy force (N)	I_{yy}	Glider moment of inertia about the y axis (kg m^2)
C_{d_hull}	Hull drag coefficient (-)	I_{zz}	Glider moment of inertia about the z axis (kg m^2)
C_{d_wing}	Wing drag coefficient (-)	I_{xy}	Cross product, moment of inertia (kg m^2)
C_{l_hull}	Hull lift coefficient (-)	I_{zx}	Cross product, moment of inertia (kg m^2)
C_{l_wing}	Wing lift coefficient (-)	I_{yz}	Cross product, moment of inertia (kg m^2)
D_{wing}	Wing drag force (N)	K	Torque about the glider x axis (Nm)
D_x	Hull drag force x direction (N)	l	Glider length (m)
D_z	Hull drag force z direction (N)	L_{wing}	Wing lift force (N)
F	Force (N)		
$\underline{g}(\eta)$	Gravitational and buoyancy vector (N)		

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M	Torque about the glider y axis (Nm)
M	Mass matrix (kg)
M_A	Added mass matrix (kg)
m	Glider mass (kg)
M_L	Hull torque about the submarine x axis (Nm)
N	Torque about the glider z axis (Nm)
p	Angular velocity about glider x axis (rad/s)
q	Angular velocity about glider y axis (rad/s)
r	Angular velocity about glider z axis (rad/s)
u	Velocity glider x direction (m/s)
v	Velocity glider y direction (m/s)
v_1	(u, v, w) (M/s)
v_2	(p, q, r) (Rad/s)
w	Velocity glider z direction (m/s)
W	Gravity force (N)
X	Force component in glider x direction (N)
XB	Center of buoyancy (m)
XG	Center of gravity (m)
X_u	Added mass (kg)
Y	Force component in glider y direction (N)
Z	Force component in glider z direction (N)
α	Angle of attack (rad)
δ	Hydroplane mechanical angle (rad)
δ_e	Effective rudder angle (rad)
δ_h	Water inflow angle (rad)
θ	Glider pitch (rad)
ρ	Water density (kg/m ³)
τ	Torque (Nm)
ϕ	Glider roll (rad)
ω	Angular velocity (rad/s)

1 Introduction

The exploitation of the oceans and seas is of great importance in today's world in terms of transportation, trade, food and pharmaceutical resources, mineral resources and coastal security [1]. Underwater glider vehicles are widely used in the monitoring, exploring and studying oceans as well as the understanding of global oceanographic phenomena. Underwater gliders are a type of unmanned vehicle that moves slowly in the water with its engines controlled by buoyancy and orientation [2]. The major advantage of gliders over other drones is their low cost and high durability [3]; they have therefore become a powerful and widely used tool in the seas and oceans. According to studies on the development of research activities in the field of underwater gliders, topics such as feasibility of designing and developing an underwater gliders for various missions in maritime units, design of exterior body, implementation of automated control systems, design of propulsion systems [8–10], as well as diving and heaving, extracting and

recording sea-level data, identifying and monitoring the operations environment [11], performing rescue operations and tracking systems are always a concern [4–8]. Heretofore many researchers have investigated the parameters affecting the dynamics of glider motions, some of which are listed below [9–11]. Parsons et al. [12] are among the first to study the geometrical shape parameters of a body in 1974 and its effect on reducing drag force in an incompressible flow. The purpose of their study was to design the axisymmetric body shape with the least drag force. One of the most important results of their work was the definition of hydrodynamic characteristics for body design.

Hu et al. [13] optimized the configuration optimization of an Underwater Glider. By means of the union simulation of CFX and Matlab they showed it has a practical significance for reducing the period and cost of model experiments. In 2009, Alvarez et al. [14] optimized the shape of the smart underwater glider body to move around the snorkel depth. By changing the shape of the nose and floating tail, they were able to reduce 25% of the total resistance, which was appropriate for moving near the surface. Hussain et al. [15] studied and modeled offshore gliders at different depths and investigated on the angle control. The information obtained from modeling methods was used to design and control the gliders. MATLAB commercial software was used to obtain a mathematical model of floating-balance system, depth-balance and angle-of-motion balance. In 2012, Ghani and Abdullah [16] studied underwater glider body with depth control system. Their results showed that the optimized body was more suitable for depth control system performance. Future developments are needed to specify the hydrostatic characteristics of underwater gliders such as displacement, center of gravity, center of buoyancy, lift, angle of rotation and launch angle.

Following previous studies, Ruiz et al. [17] studied underwater gliders and their modeling in the ocean. Experiments were carried out at 15 °C in the Mediterranean, at 100 m of shore and at an approximate depth of 60 m. The results showed that underwater gliders are a valuable and practical tool for investigating air-sea interactions in abrupt mixing event and can perform data collection with remote control. In 2012, Barker [18] analyzed an underwater glider architecture and evaluated its performance for underwater applications. The scope of this study included gliders changing operating depth by pure buoyancy as well as gliders changing depth through a combination of buoyancy change and propulsion tools. In 2014, Caiti et al. [19] investigated the control of an independent underwater glider with the help of wings angle changes. The glider consisted of a ballast tank and two hydrodynamic wings that were used to change the direction.

In 2014, Yang et al. [20] investigated the thermal glider as new type of underwater glider which achieve a much longer duration and range compare to other types. In 2015, Sun et al. [21] studied the parameters of the geometric model and optimized the shape of an underwater glider body with wings. In 2016, Jeong [22] designed and investigated the control of an unmanned marine glider at high horizontal speed, and finally the engine with a horizontal speed of 2.5 knots was designed for this glider. In 2018, Chen et al. [23], hydro-dynamically analyzed a submersible glider for the role of the glider wing in a non-uniform flow. After optimizing the wing shape, the desired angle of attack was expressed at 15 to 20 degrees. In 2019, Javaid et al. [24] experimentally studied hydrodynamic factors at velocities of 0.3 to 0.7 m/s at angles of attack of 0–18 degrees. Their results were useful for designing maneuverable gliders as well as controlling of underwater gliders with wing.

Yang et al. [25] introduced neutrally buoyant hull as an effective measure to reduce this buoyancy loss. They designed and investigated a multiple intersecting spheres (MIS) pressure hull to provide neutral buoyancy, they also combined the penalty function method and multiple population genetic algorithm to minimizing the buoyancy factor which is defined as the ratio of pressure hull mass to the undeformed displacement. They claimed that the MIS can increase the buoyancy compensation by 69.69% and increase battery capacity of the glider by 12.89%. In 2020 Song, et al. [26] established an accurate energy consumption and a gliding range model of gliders to study an optimized the most influencing parameters. Their model increases the optimal gliding range by 11.97% compared with the gliding range in the actual sea trial.

According to previous studies, one of the most important issues for researchers is the control and navigation of gliders, which has been studied many times in recent years; but the first step in controlling a glider is to identify all the environmental and hydrodynamic forces affecting its motion. The effect of these forces on the underwater gliders is directly related to the body shape and gliders wings. After identifying these forces, gliders can be controlled in different environments. In this paper, studies will be performed on a specimen glider with a spherical nose. For this purpose, a model of the proposed glider was designed and then tested in the towing tank to determine its hydrodynamic coefficients. Then, in order to complete the experimental study a meta-heuristic algorithm was developed by using the results of those tests for controlling the glider movement and especially the pitching angle. Because pitching angle is strongly affected by waves and water flow [27]. This algorithm is used for controlling the glider's motion from launching into the water, to returning to the surface. The manuscript

is organized as follows. Section 2 introduces the model of problem, elaborates on the geometry and dimensions of glider. Firstly, we present the equipment of towing tank in Sect. 3 via figures and diagrams, and then introduce the testing methods and data processing. Next, dynamic modeling of glider movement are discussed in Sect. 4. In particular, we detail the kinematics and dynamics governing equations of the Glider motion. Afterwards, we provide hydrodynamics forces caused by hull, noses, and wings of glider as well as gravity and buoyancy. Section 5. Provides the brief summary of meta-heuristic algorithm followed by its flowchart. The discussion based on the investigation of impact of major parameters on the hydrodynamics coefficients of the underwater glider is given in Sect. 6. Finally, Sect. 7 concludes this work.

2 Model of problem

As mentioned, underwater gliders are used in deep seas. The geometry of the glider will greatly influence its optimum performance. In the present study, a glider with a cylindrical body and a spherical nose was designed, which is the cone-shaped end type. According to previous studies in the world and also evaluating the operational conditions of gliders in the sea, a 1:3 scaled model has been used in this study. Accordingly, the overall length of the glider is 88 cm. As can be seen in Fig. 1, the glider consists of a 58 cm long middle body and a 30 cm long nose. In addition, to achieve the appropriate length-to-diameter ratio ($l/d = 9.76$) [28], the glider diameter of the model is 9 cm. The guiding wings of this glider are NACA0009 airfoils. This airfoil utilizes a symmetrical cross section which greatly stabilizes the glider's motion. The exact dimensions of the designed glider are given in Table 1.

In the experimental study, the examined parameters include launch velocity, launch angle and the angle of attack of wings. In addition to the mentioned parameters, the distance and position of the center of mass relative to the buoyancy center are also considered as another important parameter in controlling the gliders motion. The range of variations in these parameters is presented in Table 2 (Fig. 2).

3 Experimental study

3.1 Equipment

The system used for the test is a towing tank with length of 38 m, 3 m width and depth of 1.5 m. In addition to the traction system, the towing tank also has data measurement and reporting devices. Due to the velocity range of

Fig. 1 3D view and precise dimensions of the designed glider

Table 1 Geometric specifications of the glider

I_y ($kg.m^2$)	M (kg)	V (m^3)	Glider Diameter (m)	Glider length (m)	Airfoil length (m)	Airfoil type
0.3091	5.935	0.006068	0.09	0.88	0.395	NACA0009

Table 2 The range of variations of parameters

Parameter	Dimension	Step
Glider velocity	$[0.2, 1] m/s$	0.2
Launch angle	$[10, 80] degrees$	10
Angle of attack	$[-20, +20] degrees$	5
Wing angle	0	Constant
The distance between the center of mass and the center of buoyancy	$[-10, +10] cm$	0.02

the glider as well as the dimensions of the tank, the model is located at a distance from the wall that the effects of the wall are negligible.

To measure hydrodynamic coefficients, a six-component dynamometer is used Fig. 3. This dynamometer is equipped with different load cells, which are:

- Single point load cell for measuring drag force and sway and yaw moments
- Tensile load cell for roll moment measurement
- Rotation potentiometer to measure pitch angle

Fig. 2 Model of the underwater glider in the towing tank

Fig. 3 Dynamometer of the towing tank

measuring equipment along with their error ranges are shown in Table 3.

3.2 Test method and data processing

According to the operating conditions of the towing tank, to determine the degree of uncertainty and error of the whole measurement system, the test output data were evaluated for a zero-degree attack angle as well as a velocity of 0.2m/s. After installation and testing, the values of the forces applied to the glider in the X-direction are measured by the sensors installed in the towing tank and finally converted to the force form with the help of the conversion functions defined in the monitoring software.

For evaluation of the uncertainty, two types of uncertainty have been evaluated; in this regard, in order to assess the uncertainty of Type A (statistical), the experiments were repeated 5 times. In addition to consider the effects of various possible measurement errors (measuring

Fig. 4 Block diagram of the towing tank data collecting system

The block diagram of the towing tank data collecting system is presented in Fig. 4. The system includes power panel, drivers, motors, wagon, PLCs, computer displays, dynamometers, sensors, load cells and strain gauges, data and battery boxes, wireless transmitters and electronics devices. In addition, the technical specifications of the

instruments and methods, operator, environmental conditions), the uncertainty of Type B (non-statistical) has also been evaluated. The results are presented in Table 4. As can be seen, the overall uncertainty for the towing tank measurement system is evaluated to be 4%.

Table 3 Main equipment of towing tank with error evaluation

Equipment	Model	Capacity	Total error
load cell	C3G	10kg	$\leq \pm 0.015$
load cell	C3D	1kg	$\leq \pm 0.030$
load cell	C4	25kg	$\leq \pm 0.018$
Rotation potentiometer	BOURNS	2k Ω	$\leq \pm 0.010$
Heave motion sensor	LVDT	500mm	$\leq \pm 0.010$

After evaluating the uncertainty and ensuring the performance of the measurement system, based on the range of variations of each parameter, experimental tests are performed on the model glider; then, by processing the output data, the hydrodynamic forces on the glider are obtained. According to the determination of hydrodynamic forces and also using Eq. (1) and (2) and (3) and with respect to the wing angle and different angles of attack, the values of drag, lift and torque coefficients at various velocities are calculated for the glider nose.

$$C_D = \frac{2D}{\rho u^2 A_D} \quad (1)$$

$$C_L = \frac{2L}{\rho H \delta u^2} \quad (2)$$

$$C_M = \frac{2M_L}{\rho u^2 A} \quad (3)$$

in above equations, D , L and M , are drag coefficient, lift coefficient and torque coefficient, respectively and H is the area of the wing surface and δ is the angle between the glider body and the wing.

Fig. 5 Definition of reference frameworks, along with all degrees of freedom

4 Dynamic modeling of glider movement

4.1 Hydrostatic equilibrium

For underwater vessels, it is difficult to separate the static and dynamic aspects, as most of the two effects are always alongside. Static stability in underwater gliders, both transversely and longitudinally (rotation of longitudinal and transverse axes), requires the center of gravity to lie beneath the buoyancy center. The motion of objects within a fluid includes motion in the direction of three axes longitudinally, transversely, and vertically, which are called surge, sway, and heave, respectively, and also rotational motion around these three axes, which are called roll, pitch, or yaw, respectively (Fig. 5). Since the present model is only studied on the XZ plane, only the equilibrium in this respect has been examined. Accordingly, the center of mass and center of buoyancy are on the X-axis, and only the center of mass on this axis will be displaced to investigate its effect on the glider motion.

Table 4 Uncertainty calculated for the towing tank measurement system

Test	Data	Standard deviation	Total standard uncertainty	Uncertainty type A		Uncertainty type B	
				Average standard deviation	Uncertainty Percentage Type A	Uncertainty of sensor	Uncertainty percentage type B
Test1	-34.6866	6.65075183	4.117164502	2.974306642	0.026743066	2.846848	0.041171645
Test2	-30.0948						
Test3	-37.0353						
Test4	-30.5271						
Test5	-46.4686						
Average	-35.7625						

4.2 Kinematics and dynamics modeling of the glider

A variety of complex and nonlinear forces, such as hydrodynamic drag, damping, lift forces, Coriolis, and centrifugal forces, gravity and buoyancy, along with propulsion and environmental disturbances affect the movement of an underwater glider which ultimately makes it difficult to control its movement. Therefore, Kinematic and dynamic modeling of gliders has a great impact on the control of underwater motion.

4.2.1 Six degrees of freedom equations of gliders

To derive the 6 degrees of freedom equations, two reference coordinates are provided for the glider; one is the global fixed reference framework (W) and the other is the fixed reference framework (B) on body. The direction of the axes in both W and B frames are shown in Fig. 5. Euler relations are used to transfer each coordinate to the other 0 [29].

To obtain the 6 degrees of freedom equations, it is assumed that the coordinate system B is located on the center of the glider buoyancy, so that in this case the inertia tensor will be in diagonal form (Eq. 4).

$$I_B = \begin{bmatrix} I_{xx} & 0 & 0 \\ 0 & I_{yy} & 0 \\ 0 & 0 & I_{zz} \end{bmatrix} \quad (4)$$

Now according to the Newton and Euler equations, the six degrees of freedom equation of the glider are obtained as Eq. (5) [29]:

$$\begin{aligned} m[\dot{u} - vr + wq - x_G(q^2 + r^2) + y_G(pq - \dot{r}) + z_G(pr + \dot{q})] &= \sum X_i \\ m[\dot{v} - wp + ur - y_G(r^2 + p^2) + z_G(qr - \dot{p}) + x_G(qp + \dot{r})] &= \sum Y_i \\ m[\dot{w} - uq + vp - z_G(p^2 + q^2) + x_G(rq - \dot{q}) + y_G(rq + \dot{p})] &= \sum Z_i \\ I_x \dot{p} + (I_z - I_y)qr + m[y_g(\dot{w} - uq + vp) - z_g(\dot{v} - wp + ur)] &= \sum K_i \\ I_y \dot{q} + (I_x - I_z)rp + m[z_g(\dot{u} - vr + wq) - x_g(\dot{w} - uq + vp)] &= \sum M_i \\ I_z \dot{r} + (I_y - I_x)pq + m[x_g(\dot{v} - wp + ur) - y_g(\dot{u} - vr + wq)] &= \sum N_i \end{aligned} \quad (5)$$

4.2.2 Dynamic modeling of glider motion

Dynamic modeling is necessary to develop the algorithms for controlling and simulating of gliders motions. Considering the Newton–Euler equation with respect to the motion of a rigid object in fluids, the dynamic model of the glider motion can be considered as follows 0 [29]:

$$\underline{M}\dot{\underline{v}} + \underline{C}(\underline{v})\underline{v} + \underline{D}(\underline{v})\underline{v} + \underline{g}(\underline{\eta}) = \underline{\tau} \quad (6)$$

where $\underline{M}$ is the inertial matrix of the rigid body and the added mass, $\underline{C}(\underline{v})$ is the Coriolis matrix and the centrifuge of the rigid body and the added mass, $\underline{D}(\underline{v})$ is Damping matrix (second order and linear), $\underline{g}(\underline{\eta})$ is Gravity and buoyancy matrix, and $\underline{\tau}$ is the force/torque vector; However, $\underline{\tau}$ is considered zero in the glider. It is worth noting that in Eq. 7, surrounding impacts such as water flows and waves are not taken into account.

$$\underline{D}(\underline{v}) = \underline{D}_q(\underline{v}) + \underline{D}_l(\underline{v}) \quad (7)$$

The applied Hydrodynamic forces and torques applied to an underwater glider can be divided into added-mass and hydrodynamic damping.

4.2.3 Mass and inertia matrices

The matrix of mass and inertia includes rigid body mass and added mass 0 [29].

$$\underline{M} = \underline{M}_{RB} + \underline{M}_A \quad (8)$$

According to Eq. (9), the body mass term is written as follows:

$$\underline{M}_{RB}\dot{\underline{v}} = \begin{bmatrix} m\dot{\underline{v}}_B + m\dot{\underline{\omega}}_B \times \underline{r}_G \\ I_B\dot{\underline{\omega}}_B + m\underline{r}_G \times \dot{\underline{v}}_B \end{bmatrix} \quad (9)$$

In this equation, $\underline{r}_G$ is the position of the center of gravity of the glider in the coordinate system on the body.

$$\underline{r}_G = [x_G \ y_G \ z_G]^T \quad (10)$$

$\underline{M}_{RB}$ in Eq. (11) is expressed as follows:

$$\underline{M}_{RB} = \begin{bmatrix} m & 0 & 0 & 0 & mz_G & -my_G \\ 0 & m & 0 & -mz_G & 0 & mx_G \\ 0 & 0 & m & my_G & -mx_G & 0 \\ 0 & -mz_G & my_G & I_{xx} & -I_{xy} & -I_{xz} \\ mz_G & 0 & -mx_G & -I_{yx} & I_{yy} & -I_{yz} \\ -my_G & mx_G & 0 & -I_{zx} & -I_{zy} & I_{zz} \end{bmatrix} \quad (11)$$

The glider is symmetric on the XZ and XY planes, and with good approximation one can assume that it has symmetry on the YZ plane as well. This will dramatically reduce the computation. The mass of the rigid body is obtained as follows:

$$\underline{M}_{RB} = \begin{bmatrix} m & 0 & 0 & 0 & mz_G & -my_G \\ 0 & m & 0 & -mz_G & 0 & mx_G \\ 0 & 0 & m & my_G & -mx_G & 0 \\ 0 & -mz_G & my_G & I_{xx} & 0 & 0 \\ mz_G & 0 & -mx_G & 0 & I_{yy} & 0 \\ -my_G & mx_G & 0 & 0 & 0 & I_{zz} \end{bmatrix} \quad (12)$$

Hydrodynamic added mass is defined as follows:

$$\underline{M}_A = \begin{bmatrix} X_{\dot{u}} & X_{\dot{v}} & X_{\dot{w}} & X_{\dot{p}} & X_{\dot{q}} & X_{\dot{r}} \\ Y_{\dot{u}} & Y_{\dot{v}} & Y_{\dot{w}} & Y_{\dot{p}} & Y_{\dot{q}} & Y_{\dot{r}} \\ Z_{\dot{u}} & Z_{\dot{v}} & Z_{\dot{w}} & Z_{\dot{p}} & Z_{\dot{q}} & Z_{\dot{r}} \\ K_{\dot{u}} & K_{\dot{v}} & K_{\dot{w}} & K_{\dot{p}} & K_{\dot{q}} & K_{\dot{r}} \\ M_{\dot{u}} & M_{\dot{v}} & M_{\dot{w}} & M_{\dot{p}} & M_{\dot{q}} & M_{\dot{r}} \\ N_{\dot{u}} & N_{\dot{v}} & N_{\dot{w}} & N_{\dot{p}} & N_{\dot{q}} & N_{\dot{r}} \end{bmatrix} \quad (13)$$

According to the SNAME¹ convention, the indices of the added mass matrix is calculated using Eq. (14):

$$X_{\dot{u}} = \frac{\partial X}{\partial \dot{u}} \quad (14)$$

This article ignores the equations and relationships associated with the added mass.

4.2.4 Hydrodynamic damping matrix

Underwater hydrodynamic damping involves drag and lift forces.

4.2.5 Forces caused by wings

In order to calculate the lift and drag force applied on the guiding wings of an underwater glider, this issue is first explained in two dimensions and then in three dimensions. Due to the fact that the coefficients of lift and drag on the wings have been obtained by using the results of glider experiments in the towing tank; by using these coefficients, the lift and drag force on the wings are calculated as follows [30]:

$$L_{wing} = \frac{1}{2} \cdot \rho \cdot A_{wing} \cdot C_{l_wing} \cdot \cos \delta_e \cdot \sin \delta_e \quad (15)$$

$$D_{wing} = \frac{1}{2} \cdot \rho \cdot A_{wing} \cdot C_{d_wing} \cdot \sin^2 \delta_e \quad (16)$$

A_{wing} is the surface area of the wing in view from above, δ_e is the angle of attack of the wing with respect to the direction of velocity, which is calculated in the local coordinates as follows:

$$\delta_e = \delta - \delta_h \quad (17)$$

δ is the angle between the body of the glider and the wing in XZ plane, and δ_h is the angle between the body and the direction of the water velocity Fig. 6 that can be obtained from the following relation:

$$\delta_h = \arctan \left(\frac{v_y}{v_x} \right) \quad (18)$$

Fig. 6 Lift and drag forces of wing in two dimensions

These components are transformed into longitudinal and lateral forces and momentum in the Yaw direction:

$$F_x = -D_{wing} \cdot \cos \delta_h - L_{wing} \cdot \sin \delta_h \quad (19)$$

$$F_y = L_{wing} \cdot \cos \delta_h - D_{wing} \cdot \sin \delta_h \quad (20)$$

$$\tau = x \times (F_x, F_y, 0) \quad (21)$$

To study the forces applied to the wings in three-dimensions, it is necessary to calculate δ_h Fig. 7.

The velocity vector of water at the wing X_r position is calculated by Eq. (22):

$$v_r = -(v_1, v_2 \times x_r) \quad (22)$$

$$v_1 = (u, v, w) \quad v_2 = (p, q, r) \quad (23)$$

This velocity vector is in line with the glider hull and is perpendicular to the normal vector of wing plane.

$$v_{re} = \left(1 - \frac{NN^T}{N^TN} \right) V_r^5 \quad (24)$$

where δ_h is the angle between v_{re} and $[-1 \ 0 \ 0]^T$, which is the angle between the direction of the glider and the direction of the flow. δ_e is the angle between flow direction and the angle of attack.

4.2.6 Force caused by the hull of glider

Since the purpose is to study the glider movement on the XZ plane. Therefore, the equations of drag and lift forces, as well as torque, are found only on this plane.

¹ Society of Naval Architects and Marine Engineers, 1950.

Fig. 7 Angle of the wing in three dimensions

The drag force caused by the hull on the XZ plane is calculated as Eq. (25) [31]:

$$\begin{aligned} D_x &= -\frac{\rho}{2} A_f C_{d_hull} (u^2 + w^2) \cos \alpha \approx -\frac{\rho}{2} A_f C_{d_hull} (u^2 + w^2) \left(1 - \frac{\alpha^2}{2}\right) \\ D_z &= -\frac{\rho}{2} A_f C_{d_hull} (u^2 + w^2) \sin \alpha \approx -\frac{\rho}{2} A_f C_{d_hull} (u^2 + w^2) \alpha \end{aligned} \quad (25)$$

The lift force is applied to the center of the glider pressure by moving the hull perpendicular to the water flow. Placing this force in the center of the buoyancy creates a torsional torque around the center of the buoyancy. The lift and torque force of the hull on the XZ plane is calculated as Eq. (26) [31]:

$$\begin{aligned} Z_L &= -\frac{\rho}{2} A_f C_{l_hull} (u^2 + w^2) \alpha \cos \alpha \\ M_L &= -\frac{\rho}{2} A_f C_{M_\alpha} (u^2 + w^2) \alpha \end{aligned} \quad (26)$$

The values of drag coefficients, lift and torque related to the desired glider were obtained using experimental tests.

4.3 Gravity and buoyancy matrix

The gravitational and buoyancy vector is calculated as follows [30]0:

$$\underline{g}(\eta) = \begin{bmatrix} -(W - B) \sin(\theta) \\ (W - B) \cos(\theta) \sin(\phi) \\ (W - B) \cos(\theta) \cos(\phi) \\ y_g W \cos(\theta) \cos(\phi) - z_g W \cos(\theta) \sin(\phi) \\ -z_g W \sin(\theta) - x_g W \cos(\theta) \cos(\phi) \\ x_g W \cos(\theta) \sin(\phi) + y_g W \sin(\theta) \end{bmatrix} \quad (27)$$

Thus, the forces affecting the motion of the underwater glider are calculated.

4.4 Summarizing dynamic equations

All the above equations are for six degrees of freedom motions. While the purpose of this article is to investigate an underwater glider on the XZ plane, this would mean reducing degrees of freedom to three. Accordingly, simplifications are made to the equations that are presented in the following linear motion model on the XZ plane.

The equations used to describe gliders motion are coupled and nonlinear. Assuming that the glider does not have roll motion, the Eq. (5) can be divided into two sets of equations. Since the purpose of the present study is to study the motion of the glider on the longitudinal plane. These equations are solved by the following assumptions:

1. There is no force along the y-axis ($Y_{ext} = 0$) and therefore no displacement in this direction.
2. There is no torque around the x-axis ($K_{ext} = 0$) and therefore no rotation.
3. There is no torque around the z axis ($N_{ext} = 0$) and therefore no rotation.
4. The position of the center of gravity of the glider in the (B) coordinate system is obtained as follows:

$$r_G = [x_G \ 0 \ z_G]^T \quad (28)$$

This value is measured relative to the buoyancy center, which is the center of the coordinate system.

5. The glider is assumed to be symmetric across the plane passing through the (B) coordinate system.

5 Flowchart of the developed algorithm

As discussed earlier, the control of underwater gliders has already attracted much research interest [32–35]. In the present article, using the equations described in the preceding sections, a code is provided in MATLAB software that simulates and controls the motion of the glider from the beginning point at the water surface at a certain angle into the water until it returns back to the surface Fig. 8. The present algorithm first calculates the pitch angle and the angle of motion of the glider at each instant. In the next step, considering these two angles, it calculates all the forces and torques affecting the glider, including the forces and torques caused by the lift and hull drag, the wing and the mass of the glider; Then their effects on the glider's acceleration is determined and finally an acceptable prediction of the glider's velocity and direction changes can be obtained. So, one loop is completed and the next loop starts to do the calculations for the next time step.

Fig. 8 Schematic of the glider diving and returning back to the surface [36]

Due to the fact that there is no propulsive force, this algorithm uses a variable mass transfer inside the glider to control the glider's movement from the time it is launched into the water until it returns back to the surface. In this way, it is possible to change the position of the center of gravity relative to the buoyancy center (the origin of the local coordinates). It is important to change the position of the center of gravity so that the glider is always in line with the launch path.

Figure 9 illustrates the flowchart of the implemented program algorithm briefly. One of the most important parts of this algorithm is to calculate the accelerations of the resulting forces and torques on the buoyancy center of the glider. During the movement at each time step, the resultant of forces and torques applied to the glider at different positions of the center of mass are calculated. Then the accelerations of these forces and moments are calculated, using these accelerations, the velocities and locations of each of the mass centers are calculated. It should be noted that velocities include linear velocities along horizontal and vertical axis as well as angular velocities; and the positions also include the position along the X, Y axis, and the angular position of the glider (trim); and so the inner loop is completed. In the following, different paths of the inner loop are compared to reach the next location and each is selected closer to the conditions stated above. The glider parameters at the selected point are used as the initial value for starting the next loop. It is worth noting that among the various velocities in the applied tests, the velocity of 1 m/s has been selected for use in the algorithm.

6 Results and discussion

In this section, first, based on the data obtained from the tests, the hydrodynamic coefficients are calculated; then the results related to the dynamic modeling of the glider movement and also the results of optimization will be presented.

6.1 Results of experimental tests

Figure 10 shows the variations of the drag coefficient of the hull obtained for the glider velocity of 0.2 to 1 m/s at different angles of attack. As can be seen, the values are symmetrically distributed with respect to the zero angle of attack. As the angle of attack and glider velocity increase, the drag coefficient also increases.

Figure 11 shows the variations in the drag coefficient of the hull in terms of glider velocities. According to the symmetry shown in the figure above, at non-zero and symmetric attack angles, the amount of drag applied to the whole vessel is equivalent.

According to Fig. 12, the drag coefficient of the wings increases with increasing angle of attack, and as the drag coefficient increases, more propulsive force will be required to move the glider. The range of flow velocity variations was also considered to be 0.2 to 1.0 m/s . Increasing the angle of attack is useful for diving or heaving the glider, which requires more propulsion because of the increased drag coefficient.

Figure 13 shows the variations of the wings drag coefficient in terms of flow velocity. Compared to Fig. 10, although the total drag increases with increasing glider velocity, increasing the velocity reduces the drag of the wings. These drag variations are more tangible at larger angles of attack.

Figure 14 shows the variations in the hull lift coefficient for the velocities of 0.2 to 1.0 m/s obtained at various angles of attack. Because of the geometric symmetry of the glider, the distribution of the total lift coefficient is symmetric at the origin. In this figure, the lift coefficient is increased linearly (in positive and negative direction) by varying the angle of attack to the extent that stall prevents it from increasing. This point is approximately close to the -15 degrees angle of attack which a sudden drop in the size of the lift force occurs due to the separation of the fluid at the wings' suction surface (deceleration) and the reduction of pressure difference.

Figure 15 shows the variations in hull lift force at various angles of attack in terms of flow velocity. As it can be seen, the average of these variations is not significant for the tested velocities.

Fig. 9 An overview of the algorithm

Fig. 10 Effects of angle of attack on the drag coefficient of the hull for different glider velocities

Fig. 12 Effect of angle of attack on drag coefficient of wings for different glider velocities

Fig. 11 Effects of glider velocity on drag coefficient of the hull for different angles of attack

Fig. 13 Effect of glider velocity on drag coefficient of wings for different angles of attack

Figure 16 shows the wings lift coefficient variations at the tested angles of attack at flow velocities of 0.2 to 1 m/s. As can be seen, a large portion of the total lift is generated by the wings, which play a significant role in the glider's motion. From the comparison of Figs. 14 and 16, it can be concluded that the slight difference of Stall point indicates the effects of the glider hull.

Figure 17 shows the lift coefficients of the wings in terms of different flow velocities. It is seen that this graph is neutral to the velocity variations. This is due to the low Reynolds number (1.2×10^5 maximum Reynolds) and the closeness of velocities.

6.2 Hydrodynamic coefficients

To apply the results of the experimental tests to the code algorithm, one needs to obtain the closest regression graph to it.

6.2.1 Drag and lift coefficients of the wing

The regression graph equation corresponding to the experimental drag coefficient test of the glider at the velocity of 1 m/s is a polynomial of degree 4:

$$C_{d_wing} = 0.2579\alpha^4 - 0.0013\alpha^3 - 0.0018\alpha^2 - 0.00003\alpha + 0.0001 \quad (29)$$

Fig. 14 Effect of angle of attack on hull lift coefficient with wings for different glider velocities

Fig. 16 Effect of angle of attack on the lift coefficient of wings for different angles of attack

Fig. 15 Effect of glider velocity on hull lift coefficient with wings for different angles of attack

Fig. 17 Effects of glider velocity on lift coefficient with wings for different angles of attack

The drag coefficient of the experimental tests for the glider wings is given in Fig. 18. It is found that the regression diagram corresponding to it is in good agreement with it.

The regression graph equation corresponding to the experimental lift coefficient test of the glider at the velocity of 1 m/s is a polynomial of degree of 4:

$$C_{l_wing} = -5.537\alpha^4 - 27.38\alpha^3 + 0.4025\alpha^2 + 1.9758\alpha - 0.0016 \quad (30)$$

The lift coefficient of the experimental tests for the glider wing is shown in Fig. 19. As with the drag coefficient, here also regression graph is in good agreement.

6.2.2 Coefficients of drag, lift and hull torque

The regression graph equation corresponding to the experimental drag coefficient test of the glider at the velocity of 1 m/s is a polynomial of degree of 4:

$$C_{d_body} = \left| 3.7935\alpha^4 + 6.4306\alpha^3 - 0.2972\alpha^2 - 1.2574\alpha + 0.0045 \right| \quad (31)$$

Fig. 18 Regression graph of the drag coefficient of the wing

Fig. 20 Regression graph of the hull drag coefficient

Fig. 19 Regression graph of lift coefficient

Fig. 21 Regression diagram of the hull lift coefficient

The drag coefficient of the experimental tests for the glider hull is shown in Fig. 20. The considered regression function approximates the most important points of the experimental results well.

The regression diagram equation corresponding to the experimental lift coefficient test of the glider at the velocity of 1 m/s is a polynomial of degree of 4:

$$C_{l_body} = -0.2388\alpha^4 - 1.7958\alpha^3 + 0.0188\alpha^2 + 0.3772\alpha + 0.0005 \quad (32)$$

The lift coefficient of the experimental tests for the glider hull is shown in Fig. 21. As with the drag coefficient, here also regression graph is in good agreement.

Also, the total glider torque coefficient is about 0.0974.

6.3 Dynamic modeling of glider movement

6.3.1 Meta-heuristic optimization

Optimization methods are divided into two categories: precision algorithms and approximate algorithms. Precise algorithms are able to find the optimal solution accurately, but they are not efficient enough for complex optimization problems, and their execution time increases exponentially according to the dimensions of the problems. Approximate algorithms are able to find approximate (near-optimized) solutions in less time for difficult optimization problems. The approximate algorithms are also divided into three categories: heuristic, meta-heuristic and hybrid meta-heuristic algorithms. Meta-heuristic algorithms are one of the types of approximate optimization algorithms that can be used in a wide range of issues.

The process of designing and implementing meta-algorithmic algorithms has three consecutive sections, each of which has different steps. The first step is preparation, in which accurate knowledge of the problem must be obtained, and the objectives of the meta-algorithm design algorithm must be clearly defined according to the available solutions for this problem. The next step is called construction. The most important goals of this step are to select the solution strategy, define the selection procedure and designing the algorithm for the solution strategy. The last step is the implementation, in which the implementation of the algorithm designed in the previous step includes setting the parameters, analyzing the performance, and finally compiling and reporting the results 0 [22].

6.3.2 Input parameters selection

In any optimization problem, determining the objective functions is of great importance. In the movement of gliders, what matters is access to the required depth. Of course, along with the proper depth, the amount of horizontal movement is also very important. This section outlines the important parameters that affect glider movement, and some parameters are examined using a meta-heuristic optimization algorithm.

6.3.3 Initial launch velocity of glider

The initial velocity of glider launch is one of the most important movement parameters in gliders. In the experiments of this article, the values of 0.2, 0.4, 0.6, 0.8 and 1 m/s were examined and the hydrodynamic coefficients of each were obtained. Obviously, as the launch velocity increases,

Fig. 22 Schematic of glider Trim angle

Fig. 23 Schematic of the displacement range of the glider's center of mass relative to the origin of the coordinates connected to the buoyancy center

so does the accessibility. Therefore, in the simulation work of glider launch, the maximum velocity, i.e. 1 m/s, was selected.

6.3.4 Launching angle of glider

Due to the importance of the glider launch angle which is trim angle at the zero moment before launch in its movement path and to select an optimum ratio between displacement in both horizontal and vertical directions, 8 different launch modes were selected with angles of 10, 20, 30, 40, 40, 50, 60, 70 and 80 degrees Fig. 22. For each of these angles, location and velocity charts will be displayed in detail.

6.3.5 The glider's center of mass displacement

Due to the limited placement of various electrical and mechanical equipment inside the glider and the importance of the range of motion of the center of mass, after selecting an optimal angle for launch, the range of movement of the center of mass will be optimized as the only control parameter Fig. 23. Therefore, it is crucial to find the minimum motion of the moving mass in a way that does not adversely affect the performance of the device.

6.4 Effects of the mentioned parameters in the glider movement path

Since in this algorithm, the angle of the glider wing is always constant and equal to zero, and also due to the

Fig. 24 Variations of glider path on the XZ plane for different glider launch angles

fact that the amount of glider buoyancy is more than its weight, the most important factors that increase the depth of the glider are the glider launch angle and displacement of the center of mass. Using these two parameters, the meta-heuristic algorithm first selects an optimal launch angle and then obtains an optimal range of motion for the glider's center of gravity to obtain the best glider trajectory.

6.5 Investigating the effect of glider launch angle

6.5.1 Position analysis at different launch angles

According to Fig. 24, the maximum depth (1.26 m) is obtained at launch angle of 10 degrees. The maximum horizontal distance obtained (3.07 m) was at launch angle of 70 degrees. It should be noted that by increasing the launch angle to more than 70 degrees, there is no increase in the horizontal distance, only causing the glider to return faster to the surface. But the function of the target is depth, so with these conditions, a 10 degrees angle can be selected as the appropriate launch angle.

6.5.2 Trim chart analysis at different launch angles

To avoid sudden and infinite accelerations, conditions have been created in the algorithm so that the glider's motion is always uniform. Therefore, the angle of the glider trim should be changed slowly and with a slight slope relative to the time. The present algorithm has achieved this goal. In addition, to make the glider ready for the start of the next cycle, the glider will have a similar angle to the initial launch angle as it exits the water. According to the definition, the angle of the glider in the water, which is considered relative to the hypothetical line perpendicular to the water surface, is called the trim angle.

Fig. 25 Trim angle variations on the XZ plane in terms of variation of the glider launch angle

As can be seen in Fig. 25, most of the trim angle variations were related to the low angle launches and the least variations were occurred for the higher launch angle, which indicates that the algorithm was accountable.

6.5.3 Analysis of velocity at different launch angles

Figure 26 shows the velocity variations during movement for launch angles of 10 to 80 degrees. As can be seen in the figure, the velocity decreases with increasing depth due to the existing loss as well as the glider buoyancy. At the lowest point, only the component along the X axis has a nonzero value.

Another point to be seen in the graph is that for most of the times, the glider's velocity for the same depth is slightly slower when returning, but this difference is not significant. Also, the maximum velocity variations are for the launch angle of 10 and the lowest velocity fluctuation is for the launch angle of 80 degrees.

6.5.4 Angular velocity analysis at different launch angles

As the glider moves, the center of mass continuously changes to keep the glider in the desired direction, the angular velocity will also change several times. As can be seen in Fig. 27, at low-angle launches, the increase in angular velocity and its permanent variation in deep water are large enough to keep the glider in motion, in fact it can be said that the launch angle is inversely related to the angular velocity size and the amount of its fluctuation. As the launch angle increases, the intensity of the oscillations

Fig. 26 Linear velocity variations on the xz plane in terms of the glider launch angle variation

Fig. 27 Angular velocity variations on the XZ plane with respect to glider launch angle

decreases until at large launch angles, the oscillations and variations in angular velocity are greatly reduced, and the magnitude of these oscillations reaches their lowest values from mid-depth to maximum depth.

6.5.5 Analysis of range of mass center displacement

To investigate the displacement of the center of mass, the range of its variations relative to the buoyancy center (origin of the coordinate system) is divided into negative values and positive values. Since the developed numerical algorithm is a passive algorithm and the displacement of the center of mass is considered as the only control parameter, the output results show that changing of the center of mass displacement domain in the

Fig. 28 Variations of glider path in terms of variations in the center of mass displacement in its negative part

negative section has a significant effect on the operating depth and glider movement. Accordingly, to find the lower bound of the optimal range, studies for several intervals of changes include, $[-0.045, 0.1]$, $[-0.05, 0.1]$, $[-0.055, 0.1]$, $[-0.06, 0.1]$, $[-0.08, 0.1]$ and $[-0.1, 0.1]$ have been performed. As shown in Fig. 28, the depth of the glider changes for each interval. These changes are such that the operating depth increases to the range $[-0.045, 0.1]$, then decreases slightly with the selection of the range $[-0.045, 0.1]$, so the range $[-0.045, 0.1]$ is the optimal range and (-0.045) is selected as the lower bound.

In the next step, the glider's performance has been re-evaluated in order to achieve the upper bound of the performance range by examining the changes in the positive part of the displacement domain. For this part, the intervals $[-0.045, 0.080]$, $[-0.045, 0.085]$, $[-0.045, 0.090]$, $[-0.045, 0.095]$ and $[-0.045, 0.1]$ are considered. According to Fig. 29, changes in the range of motion of the center of mass in the positive part have very little effect on changing the functional depth of the glider, so it can be ignored. But the change in horizontal distance is noticeable and upper bound of 0.085 m and 0.095 m in the center of mass displacement domain, get the most horizontal distance traveled. Since the reduction of the space occupied inside the gliders hull is very important the upper bound of 0.085 is the acceptable value. Therefore, the $[-0.045, 0.085]$ can be selected as the optimal domain. It is noteworthy that glider is not well controlled at values below 0.04 m. The variations in the position of the center of mass have been applied in the numerical code with 0.01 m step.

Finally, it can be stated that the maximum depth and horizontal distance are obtained at a launching angle of 10 degrees and a displacement interval of $[-0.045, 0.085]$ m.

Fig. 29 Variations of glider path in terms of variation of the center of mass displacement in its positive part

The maximum depth reached by the glider is 2.22 m and the maximum distance moved along the X axis is 2.47 m.

7 Conclusion

In this experimental and numerical paper, which is a starting point for a further studies, an underwater glider with a spherical nose has been modeled. In the experimental section of the paper, the tests on the glider movement within the towing tank were studied to investigate the effective hydrodynamic coefficients on an experimental model. In the following, a meta-heuristic algorithm was used to control an underwater glider. In the coding section, the algorithm was designed to maintain the trim angle of the glider in a proper direction. Experimental results showed that with increasing glider velocity, the drag coefficient of whole body of glider increases and the maximum value occurs at velocity of 1 m/s, the lift coefficient also increases up to the velocity of 0.8 m/s and then decreases. The maximum value of lift coefficient belongs to AOA of 20 degree. In order to obtain the optimal ratio between the heaving depth and the horizontal distance, a program was developed with the optimal algorithm by checking the glider launch angle. Finally, the 10° launch angle was chosen as the optimum angle. Analyses were also performed to determine the center of mass displacement range and the interval $[-0.045, 0.085]$ was selected as the optimal displacement range. It is worth mentioning that due to the dimensional limitation of the towing tank and also the carriage capacity, it is recommended that the tests be performed in a towing tank with larger

dimensions and sea-like environment in order to achieve a more realistic simulation of glider performance. It is also possible to use noses with different geometries, such as conical and elliptical, and compare the displacement of different noses with each other and find the optimum geometry for underwater gliders.

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Compliance with ethical standards

Conflicts of interest The authors declare that they have no conflict of interest.

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