a NATO Research Centre
un Centre de Recherche de l'OTAN

PARTNERING FOR MARITIME INNOVATION

Reprint Series NURC-PR-2012-002

Redesigning the SLOCUM glider for torpedo tube launching

Alberto Alvarez

April 2012

Originally published in:

IEEE Journal of Oceanic Engineering, Vol. 35, No. 5, October 2010, pp. 984-991.

About NURC

Our vision

- To conduct maritime research and develop products in support of NATO's maritime operational and transformational requirements.
- To be the first port of call for NATO's maritime research needs through our own expertise, particularly in the undersea domain, and that of our many partners in research and technology.

One of three research and technology organisations in NATO, NURC conducts maritime research in support of NATO's operational and transformation requirements. Reporting to the Supreme Allied Commander, Transformation and under the guidance of the NATO Conference of National Armaments Directors and the NATO Military Committee, our focus is on the undersea domain and on solutions to maritime security problems.

The Scientific Committee of National Representatives, membership of which is open to all NATO nations, provides scientific guidance to NURC and the Supreme Allied Commander Transformation.

NURC is funded through NATO common funds and respond explicitly to NATO's common requirements. Our plans and operations are extensively and regularly reviewed by outside bodies including peer review of the science and technology, independent national expert oversight, review of proposed deliverables by military user authorities, and independent business process certification.

NOTE: The NURC Reprint series reprints papers and articles published by NURC authors in the open literature as an effort to widely disseminate NURC products. Users are encouraged to cite the original article where possible.

Peer-Reviewed Technical Communication

Redesigning the SLOCUM Glider for Torpedo Tube Launching

A. Alvarez

Abstract—**Launching gliders from a submarine torpedo tube is of special interest for military operations. This is not currently possible because the wing span needed to achieve a good gliding performance is twice the standard diameter of submarine torpedo tubes. To fit lifting surfaces into small and nonconventional volumes in missiles and unmanned aerial vehicles (UAVs), retractable, compliant, and inflatable wings have been proposed by some researchers. Unfortunately, applying these solutions to underwater gliders would result in complicated wing devices or would require substantial modification to the vehicle. Lowering the wing aspect ratio while keeping constant the initial wing surface would be easier to implement, however, this would substantially degrade glider lifting performance. A possible alternative is the use of ring wings. This study investigates the hydrodynamic properties of a glider equipped with a ring wing specifically designed to fit into a torpedo tube. Specifically, a panel method is employed to compute the lift, induced drag and moment coefficient of a glider with different wing configurations. Modeled results are first compared with experimental data in the case of a glider with standard wing configuration. This study is performed on the Slocum glider due to the availability of experimental data. A numerical study is made of the Slocum glider equipped with a low aspect wing and with a ring wing. Results confirm the degradation of lifting performance of the low aspect ratio configuration. On the other hand, numerical results predict that similar gliding performance can be achieved with a Slocum glider equipped with a ring wing sized to fit the vehicle into a torpedo tube. Results encourage follow-up experimentation of these close lifting surfaces in underwater glider technology.**

Index Terms—**Panel methods, ring wing, torpedo tubes, underwater gliders.**

I. Introduction

RECENT developments in underwater technology have brought new paradigms to ocean exploration. Networking is one of these paradigms. The underlying idea is that the most efficient and effective way to explore and monitor marine areas is with a fleet of autonomous underwater platforms operating in a coordinated and adaptive manner. Gliders and autonomous underwater vehicles (AUVs) constitute the nodes of such a wide area observation network.

Gliders are unmanned underwater vehicles designed to observe vast areas of the interior ocean [1]–[3]. Gliders make use of their hydrodynamic shape and wings to induce horizontal motions while controlling buoyancy. Buoyancy control also allows for vertical motion in the water column. In summary, buoyancy changes and their hydrodynamic shape allow gliders to carry out zigzag motions between the surface and a predetermined depth with a net horizontal displacement. The nominal horizontal speed is about 2 km/h. Coastal versions of gliders operate between 30- and 200-m depth while deep gliders can reach depths of 1500 m. Gliders have an endurance of one to several months, covering distances of thousands of kilometers. Recently, a glider crossed the Atlantic Ocean ($\sim$5300 km) in a seven-month mission [4].

There is a growing interest in glider technology by naval forces. The existence of marine regions to which access is denied or restricted for political or environmental reasons, such as disputed territorial waters or dangerously exposed waters adjacent to a severely threatened coastline, calls for persistent surveillance and/or monitoring. Knowing and understanding the environment is a critical element for successful naval operations. Among other applications, gliders are useful platforms to timely characterize denied areas due to their long-range and endurance capabilities. Recently, the U.S. Navy awarded a contract to the glider manufacturer Webb Research Corporation-Teledyne Brown Engineering, Inc. (Falmouth, MA) to design a littoral battlespace-sensing glider [5]. The design would be based on the existing Slocum glider commercialized by the same company [6, Fig. 1]. A fleet of up to 150 vehicles would be operated from T-AGS60 Pathfinder survey ships [5].

Operating gliders from submarines represents a step forward to embedding this technology into naval operations. Unlike surface ships, submarines are stealth platforms that could transit denied areas while releasing a glider fleet. This would substantially speed up the positioning of gliders in restricted areas. First attempts to launch gliders from submarines include a Slocum glider launched from the Dry Deck Shelter (DDS) mounted on the USS Buffalo (SSN-715) in 2006 [7]. DDS are special modules to allow divers to exit from a submarine when submerged. These structures are about 10 m long and 3 m in diameter, and host submarines must be adapted to accommodate them on deck. A diver team supported the glider deployment from the DDS.

From a logistic point of view, the simplest procedure to launch objects from a submarine is by using its torpedo tubes. These are tubular structures with standardized sizes; for the North Atlantic Treaty Organization (NATO) submarines, the dimension is 0.533-m diameter and 7-m length. Present tube

Manuscript received March 04, 2010; revised June 22, 2010; accepted June 24, 2010. Date of publication October 18, 2010; date of current version November 30, 2010.

Associate Editor: H. Maeda.

The author is with the NATO Undersea Research Centre (NURC), 19126 La Spezia, Italy.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JOE.2010.2057170

designs allow for launching a wide variety of weapon types and configurations such as mines and missiles. Weapon ejection is enabled with different mechanisms such as air impulses, hydraulic discharges, or mechanical rams [8]. Unfortunately, launching gliders from torpedo tubes is not currently feasible because the standard diameter of the tubes is half the span of the lifting surfaces of existing gliders. Thus, a redesign or a modification of the gliders' lifting surfaces is required to allow their deployment from submarine torpedo tubes.

Foldable wings have been extensively employed in tube launched missiles [9]. In this approach, retractable wings remain folded until the vehicle leaves the launching tube. This technology may be of limited applicability in the case of gliders. Rigid foldable wings are built with many complicated parts such as mechanical hinges, rollers, cables, springs, and latches, thereby substantially increasing the vehicle's complexity and weight [10]. Conversely, glider wings are designed to be simple thin plane surfaces with reduced weight. In the case of the Slocum glider, wings are considered expendable parts of the platforms because they are often damaged during the recovery phase of the vehicle in adverse sea states. Inflatable wings are an alternative to rigid foldable wings [11], [12]. In this case, wings achieve rigidity through pressurized air or gas. This mechanism would require the incorporation of pressurization systems to keep wing rigidity at extreme external pressures (up to 100 atmospheres at 1000-m depth). Compliant wings represent the newest mechanical approach to fit lifting surfaces into small and nonconventional volumes during storage [13]. They take advantage of flexible properties of certain materials to overcome many of the problems associated with rigid foldable wings [14]. Compliant wings are receiving substantial attention in the design of modern unmanned aerial vehicles (UAVs) but their performance in the underwater environment is still unknown.

Hydrodynamics could offer alternatives to mechanical solutions to fit a glider into a submarine torpedo tube without degrading the vehicle performance or increasing its complexity. Reducing the aspect ratio of the wings is the simplest solution. This approach was implemented for launching a Slocum glider from a torpedo tube by Rodgers *et al.* [15]. In this case, a Slocum glider was equipped with low aspect ratio wings to demonstrate the concept of a new launch system called Murula, designed to deploy unmanned sensors and vehicles from torpedo tubes of Collin class submarines. This is presently an active areas of research at the Australian Defence Science and Technology Organization (DSTO, Canberra, A.C.T., Australia) [16]. Unfortunately, lowering the aspect ratio significantly degrades the lifting capabilities of the wing, leading to the search for a better solution, possibly offered by ring wings. These are curved lifting surfaces wrapped around the body providing optimum storage. Ring wings were extensively tested in the past as lifting and stabilization surfaces for missile navigation [17]. Experimental studies demonstrated that the aerodynamic performance of ring wings is comparable to planar lifting surfaces for subsonic speeds but degraded with higher speeds [17]. Ring wings have also been proposed for marine environments to increase the underwater flight performance of torpedoes and missiles [18]. Currently, ring surfaces are mostly employed like stabilizing mechanisms at the rear part of autonomous underwater vehicles, substituting traditional planar fin configurations. For underwater gliders, lifting concepts based on closed wing geometries have been proposed by August [19] for a large scale underwater glider envisioned to transport military and commercial hardware, equipment or personnel. In his proposal, a nonplanar joined wing was suggested instead of a ring wing.

Fig. 1. Slocum glider recently acquired by NURC. The picture shows the Slocum glider with the standard wing configuration. A glider has a hull length of 1.79 m and a diameter of 0.213 m.

This paper investigates whether a glider can operate with a ring-wing configuration dimensioned to fit into a submarine torpedo tube. The study focuses on the Slocum glider, which is presently one of the most popular glider platforms used by navies. Extrapolation of procedures and results to other glider vehicles is straightforward. The paper is organized as follows. Section II describes the mathematical framework considered in the study while the computational approach is detailed in Section III. Section IV reports the results obtained for lift, drag, and moment coefficients for the standard Slocum wing, low aspect ratio wing, and ring-wing configurations. Finally, Section V discusses and concludes the work.

II. Mathematical Formalism

A Slocum glider (Fig. 1) moves with a small angle of attack (AoA) in an incompressible, irrotational, and inviscid fluid. The glider has a hull length of 1.79 m and a diameter of 0.213 m. This hull is formed by a frontal ellipsoidal section of 0.21-m length, a central cylindrical part of 1.21 m, and second ellipsoidal portion of 0.37 m at the rear part of the body. The wings, located at 0.76 m from the nose, have a total surface of 0.0972 m^2 and a wing span of 0.99 m. Their tip and hull chords are 0.145 and 0.11 m, respectively. The wing has swept angles of 0.77 and 0.72 rad at the leading and trailing edges. The resulting aspect ratio (AR) is 6.5.

In this study, the Slocum glider is hydrodynamically modeled by a nonlifting central body with attached lifting surfaces of zero thickness. This mathematical framework is justified on the basis of wind tunnel measurements, which show that the total lift in the Slocum glider is mostly generated by the wings for small

AoAs [20]. The contribution of the lift induced by the fuselage only becomes significant for AoA bigger than 0.21 rad (12°). On the other hand, in-water flight tests reveal that steady glides of the Slocum glider are usually characterized by small AoAs (0.034–0.052 rad, i.e., 2°–3°) [21]. The thin plate structure of the wings used in the Slocum glider thus justifies the zero thickness assumption of the lifting surfaces. Finally, the consideration of an inviscid, irrotational, and incompressible fluid is reinforced by the excellent agreement found between fully viscous and inviscid numerical computations of the subsonic flow over missile forebodies, flying at Reynolds numbers and AoAs similar to those considered here [22].

Under the physical assumptions considered, the flowfield can be described by a velocity potential $\phi(x,y,z)$ satisfying the Laplace equation

$$\nabla^2\phi(x,y,z)=0. \tag{1}$$

With boundary conditions imposing zero normal flow across the body solid surfaces

$$\nabla(\phi+\Phi_\infty)\hat{n}=0 \tag{2}$$

with Φ_∞ and $\hat{n}$ being the velocity potential of the unperturbed incident flow and the normal to the body surface, respectively. Besides the radiation condition

$$\lim_{r\to\infty}\nabla\phi\to 0 \tag{3}$$

where $r=\|\vec{x}-\vec{x}'\|$ must be held. The solution of (1)–(3) can be expressed in terms of source singularities distributed over the fuselage and vortices over wing and wakes. The strength of these elementary solutions is obtained from applying boundary condition (2)

$$-\frac{1}{4\pi}\iint_{\text{Hull}}\sigma(\vec{x})\nabla\left(\frac{1}{r}\right)\hat{n}'dS - \frac{1}{4\pi}\iint_{\text{wing+wake}}\frac{\vec{\gamma}(\vec{x})\times\vec{r}}{r^3}\hat{n}'dS=-\nabla\Phi_\infty\hat{n}' \tag{4}$$

where σ and $\vec{\gamma}$ are the strength of sources and vortex densities, respectively, $r=\|\vec{x}-\vec{x}'\|$ with $\vec{x}$ representing the source or vortex position vector, and $\vec{x}'$ and $\hat{n}'$ are an arbitrary position vector on the vehicle surface and the normal vector to the vehicle surface corresponding to this location, respectively. The solution of (4) is not unique unless a value of the circulation Γ in the lifting surfaces is selected. This is done using the Kutta condition that states that the flow leaves the sharp trailing edge of an airfoil smoothly and with finite velocity. This condition is implemented imposing a zero value to the strength of the vortices located at the trailing edge of the lifting surfaces.

III. Computational Method

A panel method is programmed to solve the Laplace equation (1) for the velocity potential over the glider body and wings. The panel model used here for the nonlifting part of the glider is derived from the panel code developed and validated in [23]. This model follows the work of Hess and Smith [24], distributing singularities with constant strength over each panel on the fuselage. Impermeability condition (4) is forced at the collocation points positioned at the center of the fuselage panels. The panel model for the fuselage is coupled to a vortex lattice method (VLM) where vortex rings are employed to model wings. Following the approach described in [25], the wing is also divided into panels. The leading segment of the vortex ring is placed on the panel's quarter chord line and the collocation point placed at the center of the three-quarter chord line. To satisfy the Kutta condition, vortices of the trailing panels are canceled by aligning the wake vortex panels parallel to the local streamlines and their strengths equal to the strengths of the trailing panels [25]. Condition (4) is then discretized using N and M source and vortex panels respectively, and applied to each ith collocation point

$$\frac{1}{4\pi}\sum_{j=1}^{N}\frac{\sigma_j S_j\vec{r}_{ij}\hat{n}_i}{r_{ij}^3}+\sum_{j=1}^{M}\Gamma_j\vec{v}_{ij}\hat{n}_i=-\nabla\Phi_\infty\hat{n}_i,\quad i=\{1,\ldots,N+\mathrm{M}\} \tag{5}$$

where $r_{ij}=\|\vec{x}_j-\vec{x}_{ci}\|$ with $\vec{x}_j, j=\{1,\ldots,N\}$ is the location of the jth panel on the fuselage with an area S_j and unknown source strengths σ_j, $\vec{x}_{ci}$ and $\hat{n}_i$ are the locations of the collocation points over the fuselage/wings and corresponding normal vectors to the solid surface, and Γ_j and v_{ij} are the unknown circulation of the jth vortex ring, $j=\{1,\ldots,M\}$, and the velocity generated at the ith collocation point by the jth vortex ring with unit circulation ($\Gamma_j=1$), respectively. Equation (5) results in a system of $(N+M)^2$ linear equations for the source strengths and vortex circulations.

IV. Results

A. Numerical Model Validation

Numerical computations of the lift (C_L), drag (C_D), and pitch moment (C_M) coefficients of the Slocum glider have been compared with and contrasted against wind tunnel measurements reported by Berman [20] and estimations obtained by Graver *et al.* [21] from parameter identification analysis using in-water flight tests with real gliders. Following the criterion of Berman [20], coefficients C_L and C_D are normalized by the square length of the hull while C_M is referred to the geometrical center of the hull (located at 0.87 m from the body nose) and normalized to the cube of the body length. Values from [21] are accordingly rescaled because in that work the glider's frontal area was taken as reference area for coefficient normalization. The purpose of the comparisons is to evaluate if the proposed numerical model produces results in the range of acceptance determined by existing measurements and estimation approaches. Fig. 2(a) displays the mesh generated for the Slocum glider body. This mesh is constituted by 1054 quadrilateral and triangular panels on the hull and 216 quadrilateral panels for the wing. The resulting grid discretizes the body with a resolution of about 0.04 m. The number of panels is determined after numerical convergence of computed values is obtained.

Fig. 2(b) compares the computed C_L with wind tunnel measurements by Berman [20] and estimations by Graver *et al.* [21]. Unlike for C_D and C_M, Graver *et al.* [21] do not provide an empirical estimation of C_L but a value resulting from the analysis of aerodynamic reference data, computational fluid dynamics

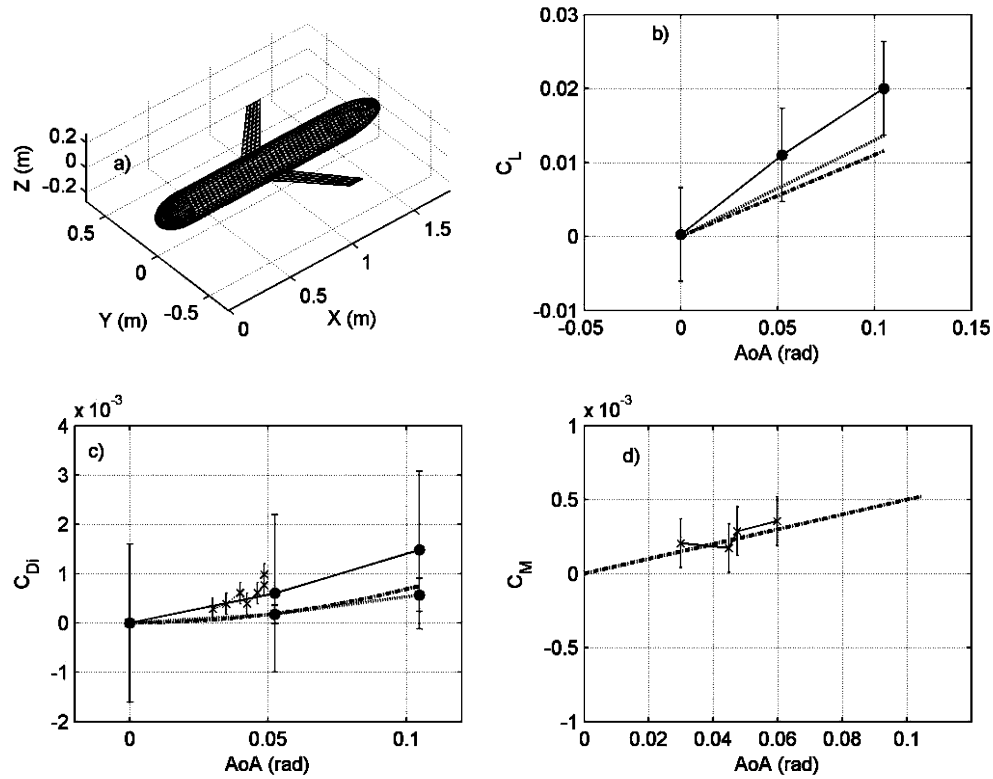

Fig. 2. (a) Meshing of the Slocum glider surface with standard wing configuration. (b) Lift coefficient from [20] (circled solid line), [21] (dotted line), and computed by the panel method (dashed–dotted line). (c) Induced drag coefficient inferred from [20] (squared–dotted line) and computed by the panel method (dashed–dotted line). Circled and crossed lines are the drag coefficients resulting from subtracting the base drag, obtained from [20] and [21], respectively. (d) Moment coefficient estimated by Gravert *et al.* [21] (crossed–solid line) and computed with the panel method (dashed–dotted line).

(CFD) computations from Humphreys *et al.* [26], and preliminary wind tunnel measurements. Results indicate that the numerical model slightly underestimates measured and estimated C_L. The slope $C_{L\alpha}$ determines the linear relationship between C_L as a function of the AoA and it is 0.11 rad^{-1} for the present numerical case, 0.14 rad^{-1} for lift measurements in the wind tunnel [20], and 0.13 rad^{-1} for the estimations given by Graver *et al.* [21]. Values of C_L measured at AoA ranging from 0 to 0.315 rad (from 0° to 18°) at intervals of 0.052 rad (3°) were used to determine $C_{L\alpha}$ from wind tunnel experiments [20]. This provides an estimation of $C_{L\alpha}$ more robust than the slope determined directly from the first two measured values displayed in Fig. 2(b) (0.18 rad^{-1}). This discrepancy is assumed to have originated from uncertainties inherent to the measurement. For AoAs smaller than 0.052 rad (3°), numerical results are consistent with reported measurements and estimations.

The developed numerical model can only estimate the induced drag C_{Di}, discarding other sources of drag present in [20] and [21]. To make comparisons feasible, numerical C_{Di} is first referred in Fig. 2(c) to the drag coefficient resulting from subtracting the drag measured at zero AoA (base drag or zero-lift drag) from the drag measured at nonzero AoAs. An important contribution of the induced drag on the resulting drag coefficient is expected. For this reason, the notation C_{Di} is employed in the vertical axis of Fig. 2(c), but it should be stressed that the experimental drag coefficient obtained from the procedure just described [circled and star lines in Fig. 2(c)] includes other drag contributions, not just the induced drag. Its consideration in Fig. 2(c) is due to a wish to provide a reference to the computed induced drag as well as a comparison with the drag values obtained from [20] and [21].

A more appropriate comparison of the numerical induced drag can be seen when the measured lift is employed to derive it. Specifically, an empirical induced drag is obtained from

$$C_{Di} = \frac{C_L^2}{\pi \mathrm{AR} e} \tag{6}$$

where e is a wing efficiency factor that accounts for taper ratio and fuselage effects on the wing. A reasonable estimate of this factor for a large range of taper ratios and sweep angles is given by Corke [27]

$$e = 0.98 \left[1 - \left(\frac{d}{b}\right)^2\right] \tag{7}$$

with d/b being the ratio of the fuselage diameter (d) to the wing span (b). Notice that coefficients in (6) refer to the gross wing area, the product of the wing span, and the mean chord, thus appropriate forward and backward rescalings are applied. A good agreement is found in Fig. 2(c) between computed numerical values and the empirical C_{Di} derived from wind tunnel measurements of Berman [20].

Only values of C_M obtained by Gravert *et al.* [21] from in-water flight tests with real gliders are used for comparison with numerical results. This is due to the technical difficulties discussed by Berman [20] to measure C_M with the employed experimental setup, resulting in a substantial degradation in the estimation of this coefficient. Similar to the previous case,

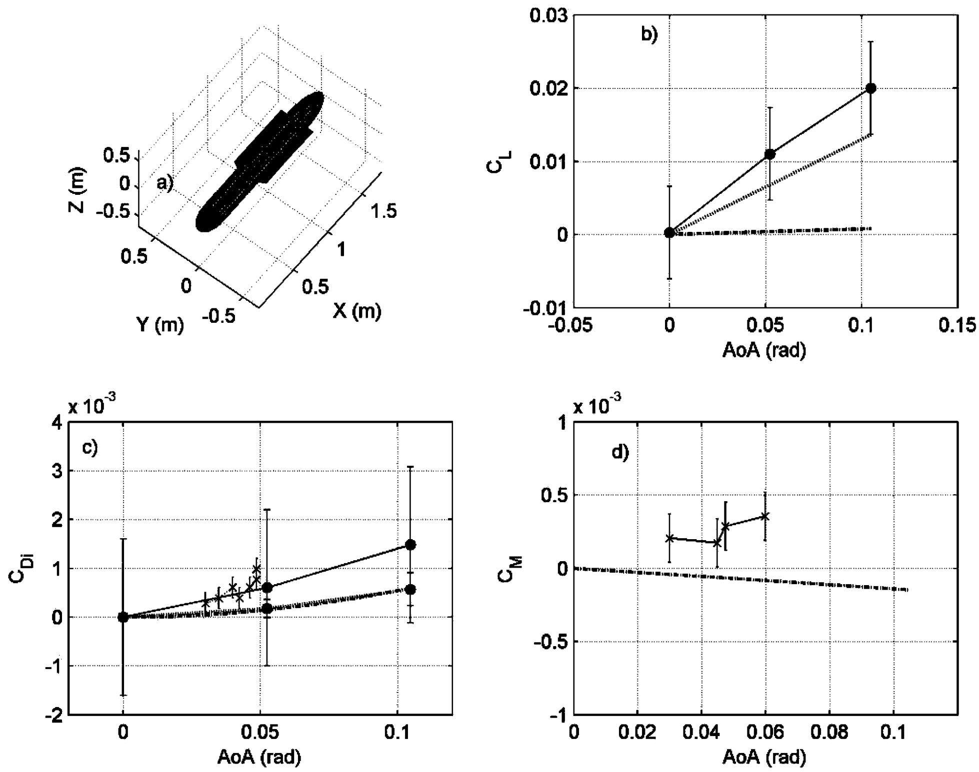

Fig. 3. (a) Meshing of the glider design suggested in [15]. (b) Lift coefficient from [20] (circled solid line), [21] (dotted line) and computed by the panel method (dashed–dotted line). (c) Induced drag coefficient inferred from [20] (squared–dotted line) and computed by the panel method (dashed–dotted line). Circled and crossed lines are the drag coefficients resulting from subtracting the base drag, obtained from [20] and [21], respectively; (d) Moment coefficient estimated by Gravert *et al.* [21] (crossed–solid line) and computed with the panel method (dashed–dotted line). Notice that only coefficients obtained from the panel method (dashed–dotted lines) correspond to the glider configuration shown in (a). Measured and estimated coefficients remain those of the standard configuration and they are included to facilitate comparison.

computed C_M cannot be directly compared with the values provided by Graver *et al.* [21]. This is so because Graver *et al.* [21] estimated the total hydrodynamic moment, including the effect of wings and the moment of Munk generated by the pressure distribution over the hull. The latter has been calculated using the equilibrium vertical and horizontal speeds, 0.2 and 0.42 m·s^{-1}, respectively, provided by Graver *et al.* [21] and added masses determined numerically. The resulting moment of Munk with a coefficient slope of -0.00128 rad^{-1} was subtracted from empirical estimations to approximate the moment generated by the lifting surfaces. Fig. 2(d) reveals good agreement between computed C_M and values obtained from the reanalysis of the data provided by Gravert *et al.* [21].

B. Numerical Analysis of Low AR Design

Numerical formalism is applied to examine the performance of the Slocum glider configuration employed by Rodgers *et al.* [15]. The original wing is substituted by another with lower AR to deploy the Slocum glider from the torpedo weapons system of a Collins class submarine. Specifically, the new wing design has a semispan of 0.07 m and a chord of 0.71 m. This geometry preserves the original wing surface but significantly decreases the AR to 0.2. Like the previous case, 1054 panels are employed to mesh the fuselage while the total number of panels on the wing is 288 [Fig. 3(a)]. As would be expected from finite wing theory [25], Fig. 3(b) shows a substantial degradation in lift generation for the new configuration with respect to the original. The computed slope of the lift coefficient C_L as a function of the AoA $C_{L\alpha}$ is 0.0075 rad^{-1} for this configuration. Fig. 3(c) and (d) shows computed C_{Di} and C_M, respectively. Notice the reduction in magnitude and negative sign of the former, which is a direct consequence of the decrease in lift and the relocation of the wing aerodynamic center, being now ahead of the body center of geometry.

C. Numerical Analysis of Ring-Wing Design

A Slocum glider with a ring-wing system is proposed in Fig. 4(a). Specifically, an elliptical ring with a major semiaxis of 0.265 m and minor vertical semiaxis of 0.262- and 0.15-m chord is considered. This elliptical shape would allow fitting the Slocum glider into the standard torpedo tube taking into account the sizing of the vertical rear fin. The leading edge of the ring is located at 0.93 m from the body nose. The location and the chord have been selected to provide similar lift and pitch moment as the original glider configuration. The hull and the ring were discretized by 1054 and 176 panels, respectively. Fig. 4(b) displays the computed lift coefficient curve for small AoA. The slope of the line C_L is 0.12 rad^{-1}. This value is close to the slope of 0.094 rad^{-1} estimated by the method of McCormick [28] for an ideal combination of a circular ring wing with a centered infinite cylindrical body

$$C_{L\alpha} = \frac{4\pi(1-r^2)}{1+\dfrac{2}{\mathrm{AR}}(1-r^2)} \tag{8}$$

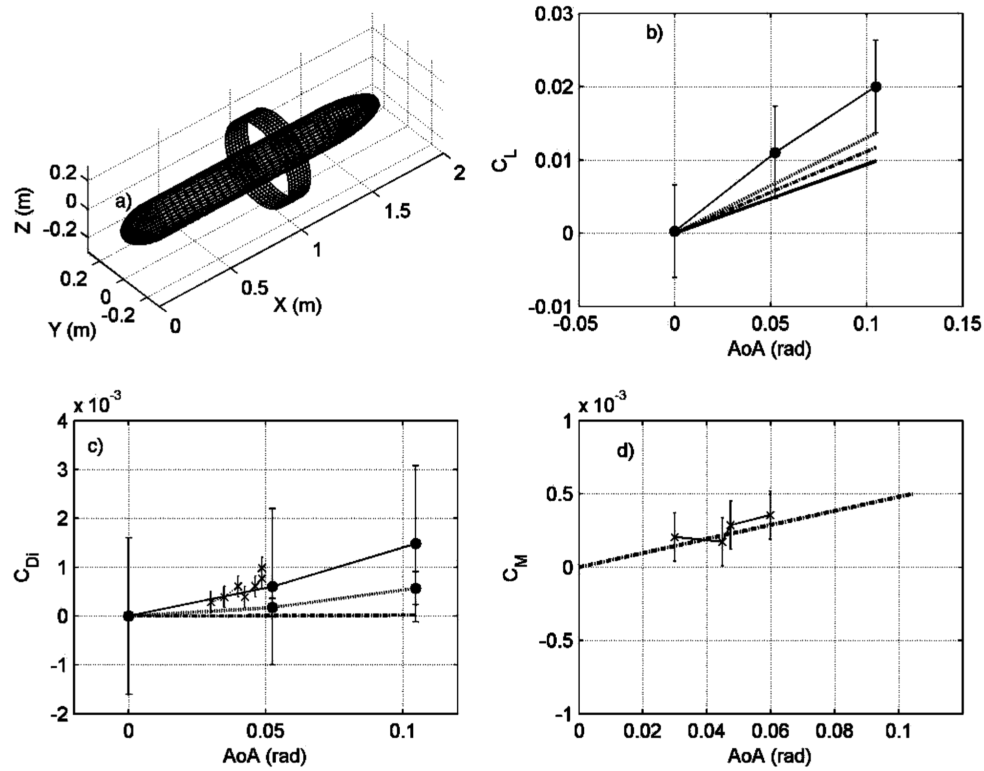

Fig. 4. (a) Meshing of the Slocum glider surface with a ring-wing configuration. (b) Lift coefficient of the ring-wing design computed by the panel method (dashed–dotted line) and McCormick's method [28] (solid line). Measured and estimated lift coefficients of the standard wing configuration are also included with the same notation as in Fig. 2. (c) Induced drag coefficient computed by the panel method (dashed–dotted line) for the ring-wing configuration. Drag coefficients measured and estimated for the standard wing configuration are displayed with same notation as in Fig. 2. (d) Moment coefficient of the ring-wing configuration computed with the panel method (dashed–dotted line) and moment coefficient estimated by Gravert *et al.* [21] for the standard wing configuration (crossed–solid line).

where r is the ratio of the body to the ring radii $R_{\text{body}}/R_{\text{ring}}$ and AR is the aspect ratio of the ring wing defined by $(8R_{\text{body}})/(\pi C)$ with C being the ring-wing chord. Notice that (8) is referred to the ring surface $S_{\text{ring}} = (\pi C R_{\text{ring}})/2$ and thus an adequate rescaling is needed to match the area reference employed in this work. Fig. 4(c) and (d) displays the induced drag and pitch moment coefficients for the ring wing. While C_M is similar to the initially required value, a remarkable reduction of C_{Di} is observed. This reduction is associated with an important elimination of the effects of wing tip vortices, which substantially contribute to the induced drag [29]. Close wing surfaces provide the minimum induced drag for a given lift and span.

V. Discussion and Conclusion

Gliders are becoming a relevant technology for ocean exploration. Autonomy, long endurance at sea, and robustness are the main factors contributing to the growing interest in their use. Likewise, navies are demonstrating a marked interest to incorporate glider technology to naval operations. However, the theater of naval operations differs substantially from civilian operations. Naval activities are increasingly focused on coastal areas to which access is often denied or restricted. Gliders used in such operations would need to be deployed by naval units far from an area of interest. Due to their low speed, a long transit time would be required for the glider to reach the desired region, a process that does not match normal tactical time scales.

Submarines are key weapon platforms in navies. They can stealthily transit denied or restricted areas with a lower probability of being detected. Besides weapons, submarines can deploy different sensors and instruments from their torpedo tubes. Unfortunately, gliders currently available in the market cannot be launched from torpedo tubes due to the size of their lifting surfaces that prevent their arrangement inside the tube. Different technological solutions are considered to overcome this problem. Some of these solutions involve complex implementation or require substantial modifications to the existing configuration of the Slocum glider, while others that can be implemented easily would substantially degrade gliding performance. This paper proposed the use of ring wings in Slocum gliders to allow launching from torpedo tubes. The substitution of the original wings of Slocum gliders by ring wings is not complicated. Investigation of the gliding performance obtained with a ring-wing glider configuration should nevertheless be conducted.

Empirical and numerical evidence suggests that the hydrodynamic description of a Slocum glider as a nonlifting central body with attached lifting surfaces of zero thickness and moving in an uncompressible fluid is realistic enough. Thus, a panel method has been employed in this study to analyze the hydrodynamic coefficients of Slocum gliders equipped with different wing configurations. The computational approach was first validated using available experimental data. Specifically, numerical estimations of the lift, induced drag, and moment coefficients

TABLE I
C_L, C_{Di}, AND C_M OBTAINED FROM THE PANEL METHOD FOR THE THREE GLIDER CONFIGURATIONS AT AN AOA OF 0.052 rad (3°). THE LAST COLUMN OF THE CORRESPONDING GLIDER NUMBERS COMPUTED USING THESE COEFFICIENTS AND A BASE DRAG COEFFICIENT (0.0024) ESTIMATED BY [21] FROM IN-WATER FLIGHT TESTS WITH STANDARD SLOCUM GLIDERS

Design \ Coefficient (0.052 rad)	C_L	C_{Di}	C_M	Glide number
Standard wing	0.0058	0.00018	0.0002	2.39
Low AR wing	0.0004	0.00014	-0.00007	0.05
Ring wing	0.0058	0.000002	0.00025	2.42

were compared against wind tunnel measurements and estimations derived from in-water flight tests. The agreement found between numerical and experimental values confirmed the adequacy of the selected mathematical and numerical framework. The numerical model was then employed to analyze the solution proposed by Rodgers *et al.* [15] based on a glider configuration with a low AR wing. Results show a substantial degradation of lift generation originated by the exposure of a bigger portion of the wing surface to the downwash effect of the tip vortex. Inappropriateness of low AR wings for gliding is well established from general wing theory. Although simple to implement on currently manufactured Slocum gliders, the wing design proposed by Rodgers *et al.* [15] could have a negative impact on gliding performance. Conversely, numerical simulations support the hypothesis that a ring-wing configuration can be designed to produce the same lift and moment of the original wing in the Slocum glider. This similarity is highly desirable because it would imply minor modifications on the Slocum glider for its implementation.

As previously noted, the induced drag is negligible for the ring-wing configuration. This could result in an improvement in gliding performance. Specifically, the performance of gliding can be determined by the glide ratio or glide number. This is defined by the ratio of the distance forward to the distance down/upward at a constant gliding speed. Alternatively, it is also the forward speed divided by the down/upward speed. Under constant speed motion, the glide ratio is numerically equal to the lift-to-drag ratio. A high glide number is always desirable. Table I shows modeled values of C_L, C_{Di}, and C_M and glide numbers for a typical AoA of 0.052 rad (3°) for the three glider configurations. Results show that a slight improvement in the gliding performance would be obtained at this AoA with the ring-wing configuration. Improvement in gliding performance introduced by ring wings would be more remarkable at high AoA, where the induced drag contributes more to the total drag. Table I also quantifies the poor gliding performance resulting from the low AR configuration.

To conclude, numerical simulations reinforce the idea that a ring-wing system with hydrodynamic properties similar to the original wing of Slocum gliders is feasible. Thus, ring wings would allow the Slocum glider to fit into submarine torpedo tubes without significantly modifying the original vehicle. The next step is to confirm this with in-water flight tests with Slocum gliders equipped with the proposed ring wing.

ACKNOWLEDGMENT

The author would like to thank Dr. E. Coiras and X. Berdaguer for their comments on the manuscript.

REFERENCES

[1] H. Stommel, "The Slocum mission," *Oceanography*, vol. 2, pp. 22–25, 1989.
[2] R. Bachmayer R., N. E. Leonard, J. Graver, E. Fiorelli, P. Battha, and D. Palley, "Underwater gliders: Recent developments and future applications," in *Proc. IEEE Int. Symp. Underwater Technol.*, Taipei, Taiwan, Apr. 20–23, 2004, pp. 195–200.
[3] D. L. Rudnick, R. E. Davies, C. C. Eriksen, D. M. Fratantoni, and M. J. Perry, "Underwater gliders for ocean research," *J. Mar. Technol. Soc.*, vol. 38, pp. 73–84, 2004.
[4] A. D. Shapiro, "Remotely piloted underwater glider crosses the Atlantic," *IEEE Spectrum*, Mar. 2010 [Online]. Available: http://spectrum.ieee.org/robotics/industrial-robots/remotely-piloted-underwater-glider-crosses-the-atlantic
[5] M. Rusling, "Gliders will aid naval research," *Nat. Defense*, Jun. 2009 [Online]. Available: http://www.nationaldefensemagazine.org/archive/2009/June/Pages/GlidersWillAidNavalResearch.aspx
[6] D. C. Webb, P. J. Simonetti, and C. P. Jones, "SLOCUM: An underwater glider propelled by environmental energy," *IEEE J. Ocean. Eng.*, vol. 26, no. 4, pp. 447–452, Oct. 2001.
[7] D. Rush, "Submarine makes first launch of an underwater glider," *Undersea Warfare*, vol. 7, no. 6, 2006 [Online]. Available: http://www.navy.mil/navydata/cno/n87/usw/issue_29/glider.html
[8] M. R. Scherr, "Undersea warfare launchers," *Naval Forces*, vol. 20, no. 4, pp. 76–81, 1999.
[9] U.S. Army, "TOW missile system," 2007 [Online]. Available: http://www.army.mil/fact_files_site/tow/index.html
[10] R. Kroyer, "Wing mechanism analysis," *Comput. Struct.*, vol. 72, no. 1, pp. 253–265, 1999.
[11] W. A. Sebrell, "Inflatable wing," U.S. Patent 3 957 232, 1976.
[12] G. Brown, R. Haggard, and B. Norton, "Inflatable structures for deployable wings," in *Proc. 16th AIAA Aerodyn. Decelerator Syst. Technol. Conf. Seminar*, Boston, MA, May 21–24, 2001, pp. 19–26, AIAA-2001–2068.
[13] S. D. Landon, S. P. Magleby, and L. L. Howell, "Preliminary concepts for deployable wings on small AUV using compliance," in *Proc. ASME Int. Mech. Eng. Congr. Expo.*, Orlando, FL, 2005, pp. 353–363.
[14] N. Lobontiu, *Compliant Mechanisms: Design of Flexure Hinges*. Boca Raton, FL: CRC Press, 2003, pp. 1–17.
[15] J. Rodgers, J. Wharington, A. Tynan, and M. Coxhead, "A concept for the deployment of unmanned maritime systems from submarines: MURULA integration impact modeling and results," in *UDT Pacific Conf.*, Sydney, Australia, 2008 [Online]. Available: http://hdl.handle.net/1947/9958

[16] "Unmanned systems the way to go for maritime applications," in *Australian Defense Science*. Canberra, A.C.T., Australia: Defense Science and Technology Organization, 2008, vol. 16, pp. 6–8.

[17] L. B. Simpson, F. A. Davis, B. G. Kruggel, and E. McLaughlin, "Conformal lifting and control surfaces for weapon stowability," in *Proc. RTO AVT Symp. Missile Aerodyn.*, Sorrento, Italy, May 11–14, 1998, pp. 6.1–6.7, Paper RTO-MP-005-06.

[18] H. August and E. Carapezza, "Ring wing for underwater missile," *J. Aircraft*, vol. 33, no. 4, pp. 830–832, 2002.

[19] H. August, "Gliding submersible transport system," U.S. Patent 7 028 631, 2006.

[20] S. Berman, "Comparison of the lift, drag and pitch moment coefficients of a Slocum glider wind tunnel model with computational results by Vehicle Control Technologies, Inc.," Princeton Univ., Princeton, NJ, MAE 222 Course Project Rep., 2003.

[21] J. G. Graver, R. Batchmayer, and N. E. Leonard, "Underwater glider model parameter identification," in *Proc. 13th Int. Symp. Unmanned Untethered Submersible Technol.*, Durham, NH, 2003, pp. 1083–1088.

[22] I. H. Tuncer, R. Marvin, and M. F. Patzer, "Numerical investigation of subsonic flow over a typical missile forebody," in *Proc. 34th AIAA Aerospace Sci. Meeting Exhibit*, Reno, NV, Jan. 15–18, 1996, AIAA paper 96-0189.

[23] A. Alvarez, V. Bertram, and L. Gualdesi, "Hull hydrodynamic optimization of autonomous underwater vehicles operating at snorkeling depth," *Ocean Eng.*, vol. 36, no. 1, pp. 105–112, 2009.

[24] J. Hess and A. M. O. Smith, "Calculation of nonlifting potential flow about arbitrary three-dimensional bodies," *J. Ship Res.*, vol. 8, no. 2, pp. 22–44, 1964.

[25] J. Katz and A. Plotkin, *Low Speed Aerodynamics*. Cambridge, U.K.: Cambridge Univ. Press, 2001, pp. 331–360.

[26] D. E. Humpreys, N. S. Smith, A. V. Roup, and K. W. Watkinson, "Validation of the hydrodynamics and maneuvering model for the Webb Research Corporation Slocum glider," Vehicle Control Technologies, Inc., Reston, VA, VCT Rep. 70, 2003.

[27] C. F. Corke, *Design of Aircraft*. Englewood Cliffs, NJ: Prentice-Hall, 2002, ch. 4.

[28] B. W. McCormick, "Effect of a center body on a ring wing," Appl. Res. Lab., Pennsylvania State Univ., State College, PA, Tech. Memo, 1959.

[29] I. Kroo, "Nonplanar wing concepts for increased aircraft efficiency," in *VKI Lecture Series on Innovative Configurations and Advanced Concepts for Future Civil Aircraft*. Rhode-St-Genèse, Belgium: VKI, 2005.

A. Alvarez received the M.S. degree in physics from the University of Santiago de Compostela, Santiago de Compostela, Spain, in 1991, the Ph.D. degree from the Physics Department, University of Balearic Island, Balearic Island, Spain, in 1995, the second Ph.D. degree in underwater robotics from the Department of Electrical Engineering, University of Pisa, Pisa, Italy, in 2004, and the D.E.A. in ocean engineering and marine technology from the Polytechnic University of Madrid, Madrid, Spain, in 2007.

Professionally, he was an Assistant Professor with the University of Balearic Island from 1995 to 1997. He received a postdoctoral position with the Physics Department, National Central University, Jhongli City, Taiwan, from 1997 to 1999, to work in underwater acoustics. In 1999, he joined the Department of Rapid Environmental Assessment, SACLANT Undersea Research Centre, La Spezia, Italy, as a Scientist. Since 2002, he has been a Scientist in the Spanish National Council Research (CSIC). In 2008, he got a special leave from CSIC to join the Department of Systems and Technology of the NATO Undersea Research Centre (former SACLANT Undersea Research Centre).

Document Data Sheet

Security Classification		Project No.
Document Serial No. NURC-PR-2012-002	Date of Issue April 2012	Total Pages 8 pp.

Author(s)

Alvarez, A.

Title

Redesigning the SLOCUM glider for torpedo tube launching.

Abstract

Launching gliders from a submarine torpedo tube is of special interest for military operations. This is not currently possible because the wing span needed to achieve a good gliding performance is twice the standard diameter of submarine torpedo tubes. To fit lifting surfaces into small and nonconventional volumes in missiles and unmanned aerial vehicles (UAVs), retractable, compliant, and inflatable wings have been proposed by some researchers. Unfortunately, applying these solutions to underwater gliders would result in complicated wing devices or would require substantial modification to the vehicle. Lowering the wing aspect ratio while keeping constant the initial wing surface would be easier to implement, however, this would substantially degrade glider lifting performance. A possible alternative is the use of ring wings. This study investigates the hydrodynamic properties of a glider equipped with a ring wing specifically designed to fit into a torpedo tube. Specifically, a panel method is employed to compute the lift, induced drag and moment coefficient of a glider with different wing configurations. Modeled results are first compared with experimental data in the case of a glider with standard wing configuration. This study is performed on the Slocum glider due to the availability of experimental data. A numerical study is made of the Slocum glider equipped with a low aspect wing and with a ring wing. Results confirm the degradation of lifting performance of the low aspect ratio configuration. On the other hand, numerical results predict that similar gliding performance can be achieved with a Slocum glider equipped with a ring wing sized to fit the vehicle into a torpedo tube. Results encourage follow-up experimentation of these close lifting surfaces in underwater glider technology.

Keywords

Panel methods, ring wing, torpedo tubes, underwater gliders

Issuing Organization

NURC
Viale San Bartolomeo 400, 19126 La Spezia, Italy

[From N. America:
NURC
(New York) APO AE 09613-5000]

Tel: +39 0187 527 361
Fax:+39 0187 527 700

E-mail: library@nurc.nato.int