Hydrodynamic Implications for Submarine Launched Underwater Gliders

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Abstract—**Underwater gliders are a type of long range unmanned vehicle that use bouyancy control and lifting surfaces to travel in a sawtooth trajectory through the water column. These vehicles are typically employed by oceanographers for environmental monitoring and also show promise as a sensor platform in military applications. This paper presents investigations of vehicle hydrodynamics relating to the deployment of a Slocum Glider from conventional submarines, where the standard vehicle was fitted with low aspect ratio wings to enable it to fit into a sabot for deployment from a 21 inch torpedo tube.**

Several non-dimensional hydrodynamic models are presented and compared with measured results from field trials in terms of lift-to-drag ratio as a function of angle of attack. The results show good agreement between the model and empirical data of the standard glider, however the experimental data showed the modified glider significantly outperformed the corresponding model prediction.

The standard glider was observed to have a maximum lift to drag ratio that was higher, and occurs at a lower angle of attack, than that of the modified glider. The modified glider was observed to have a superior lift to drag ratio for a high range of angles of attack that in practice, dominates the typical operating state. Field trials revealed the modified glider to have a 5% greater range than the standard glider. These results are contradictory to the authors' intuitive expectation, confirmed by the performance models, that the extreme reduction in the aspect ratio of the wings would introduce a significant performance degradation. In fact, the modified wings have resulted in a slight performance increase.

With respect to submarine deployment applications, it is concluded that for shallow water operation, both wing geometries have similar performance due to a sub-optimal control system. Further work, potentially involving servo-dynamic simulations, deep water trials, and further hydrodynamic modelling, would enable exploration of the significance of the modified wing performance in deep water.

Index Terms—**Underwater Glider, Low Aspect Ratio Hydrodynamics, Low Reynolds Number, Vortex Lift, Submarine.**

I. Introduction

The development and application of underwater gliders has received increasing attention in recent years. These vehicles are the only robust commercial unmanned underwater vehicle platform capable of sustained and controlled autonomous operation - including transcontinental voyages. As a class of vehicle they are distinguished by the use of gravitational potential energy for propulsion. As such, the hydrodynamic form of the vehicle is crucial to maximise the lift-to-drag ratio (L/D), and ultimately achieve efficient transfer of gravitational energy into forward velocity. This mode of locomotion reduces the vehicles energy requirement and results in a small number of moving components for propulsion. This enables underwater gliders to have a low acoustic signature and a high endurance (from months upwards), which makes them an attractive low observable sensing platform for sustained environmental sensing and Intelligence, Surveillance and Reconnaissance (ISR) activities [1].

Due to these properties underwater gliders are also an appealing platform for operations with manned submarines. The limited number of ocean interfaces on a conventional submarine leaves the 21 inch torpedo tube as the most suitable candidate for deploying underwater gliders. The physical constraint introduced by the diameter of the torpedo tube results in a practical limit on the wing span of the gliders, which is an important lifting body that contributes to the lift-to-drag ratio and therefore the locomotive efficiency of the vehicle.

This paper describes the hydrodynamic modelling and experimentation conducted to support the modification of a commercially available underwater glider, to enable it to be deployed conveniently from submarines via a sabot and through existing torpedo tubes. This modelling and analysis was primarily motivated by the need to assess the impacts on the vehicle performance resulting from the replacement of the standard, relatively high aspect ratio ($Æ$) swept back wings, with extremely low aspect ratio rectangular 'rail-like' wings (see Figure 1).

From classical aerodynamic theories such as Prandtl's lifting line theory [2] it is expected that introducing such low aspect ratio wings would have a detrimental effect on performance, since low aspect ratio lifting bodies produce high induced drag from vortex flow. Work by Lowry and Polharmus [3], Lamar [4] and empirical results form Torres and Mueller [5] predict that for very high angles of attack (α), low aspect ratio wings at low Reynolds Numbers can produce a superior lift-to-drag ratio than high aspect ratio wings. In this domain, the non-linear effects of tip vortices produce surprisingly high additional lift over the lifting surfaces.

The following sections present the authors research in

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modelling the standard Slocum Glider and one modified to adapt it to a torpedo sabot launch system (Project Murula [6], See Figure 2). Hydrodynamic models are presented of the two vehicle variants using a combination of classic inviscid flow theory, two-dimensional boundary layer flow, empirical parametric models taken from the literature, and parameters derived from system identification from experimental trials conducted by the Defence Science and Technology Organisation (DSTO). A comparative analysis of the vehicle models and empirical results is presented, as well as conclusions drawn on the performance of both the standard and modified gliders and the influence of operating depth.

A. Murula Concept

Murula [6] is a generic adapter used to encapsulate systems with varying physical parameters, while conforming to the appropriate form factor for deployment from the torpedo weapons system of a Collins class submarine. Murula consists of a flooded torpedo shaped outer case with a sensor payload encapsulated within. Deploying the sensor is performed in two stages: In the first, the Murula system and its payload are ejected from the submarine, and in the second stage the payload (in this case the Slocum glider) is deployed from the Murula system for it to complete an autonomous mission.

This system was developed by the DSTO as the experimental component of an ongoing research program to understand the abilities of conventional submarine's weapons systems to deploy a variety of different payloads, some of which being new and highly capable unmanned underwater vehicles. Such an ability has several military advantages and an understanding of the constraints of these systems is crucial for further development and enhancements to the capability of manned submarines. Many of these constraints and engineering challenges can only be realised through concept development and field trials. It is for this reason that DSTO is engaged in developing the Murula system, which has led to the research described in this paper.

II. Methodology

Typically a hydrodynamic model of an underwater vehicle is derived from composite models of the body or fuselage section, the wings, and other components which contribute to drag such as the rudder and antenna. These other components will have some contribution to drag, however obtaining accurate models for the fuselage and wings is most critical as these normally constitute approximately 80% of the total drag force [7]. From this point forward the fuselage is referred to as the body of the glider, the original configuration as the standard glider, and the version with low Æ wings as the low Æ glider.

There are a variety of methods to derive models of the vehicle's components and their contributions to lift

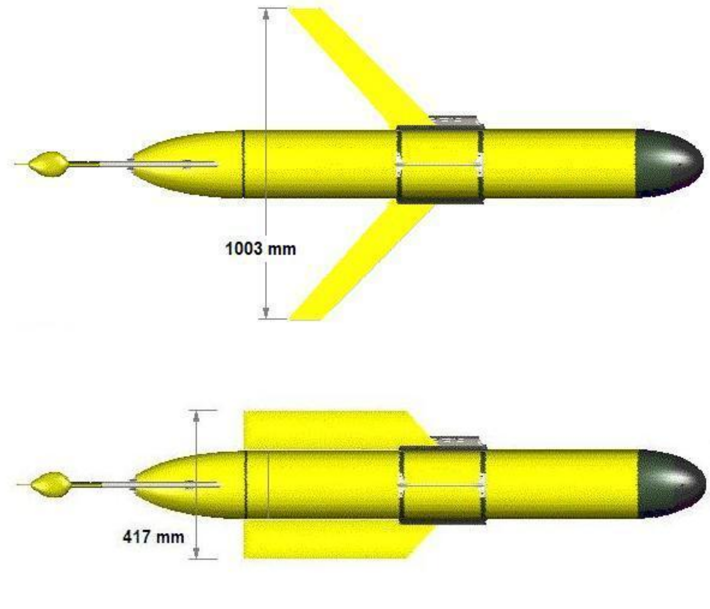

Fig. 1. Standard Slocum glider (above) and modified glider with low aspect ratio wings (below)

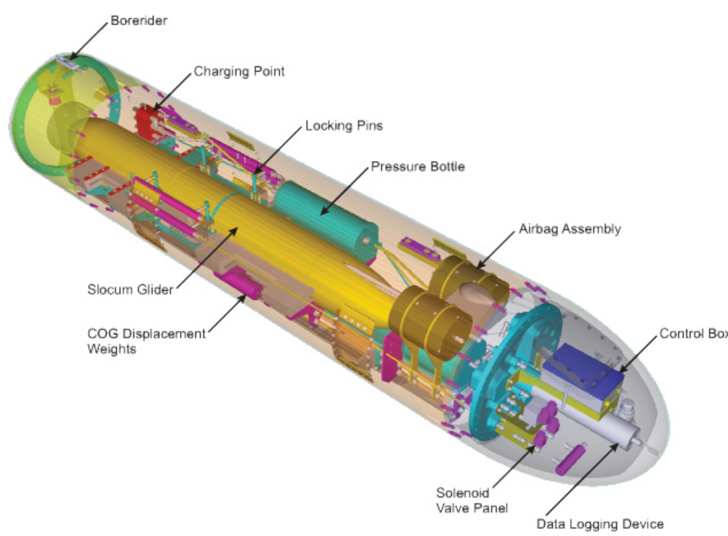

Fig. 2. Overview of the Murula deployment system and illustration of the Slocum glider's constrained wing span when encapsulated within

and drag. An example of an analytical method is that of Slender Body Approximation which models the inviscid flow around bodies with a slim length-to-diameter ratio and with only small profile gradients along the body length.

Computational methods such as Computational Fluid Dynamics enables a mathematical model of the entire vehicle to be numerically derived - where a mesh of discrete points is applied over a geometric form of the vehicle and the flow characteristics at each sample location are approximated.

Another common method is to use a combination of traditional analytical techniques with more refined and applicable co-efficients derived from measured properties of similar bodies and surfaces in similar operating environments. This semi-empirical technique allows for measured data from trials and wind tunnel tests to be incorporated into the model resulting in a potentially more accurate and higher fidelity approximation. This technique is particularly advantageous when the system being modelled contains sensitive and non-linear components. Such a method also allows for empirical results of geometric shapes with known properties to be employed in producing parametric models, where the final vehicle is a specific configuration of these known geometric shapes.

The final method discussed here is that of System Identification [8], where mathematical model parameters are determined from empirical results. This allows hydrodynamic properties of the vehicle to be determined from flight performance, however terms for components such as added mass and inertia are difficult to derive individually from this method.

The research presented in this paper employed a semi-empirical parametric model for estimating the lift and drag characteristics of the vehicle's main components, being the torpedo-shaped body and the wing. Due to the significantly different aspect ratios of the standard (high) and modified (very low) wings, different empirical models were used for these parts. These combined models estimate the hydrodynamic impact of the low $\mathcal{R}$ wings on the Slocum glider's performance.

The following section discusses low $\mathcal{R}$ aerodynamics. Following this, the vehicle models derived by the authors are presented and discussed, and finally empirical data from field trials is presented and compared with the predicted performance of the vehicle models.

III. Lift-Curve Slope Characteristics of Low $\mathcal{R}$ Wings

Analysis and comparison of the lift-curve slope (C_{l_α}) of various airfoils, and the numeric calculation of the resulting wing lift-curve slope (C_{L_α}), is an effective tool for measuring an airfoil's suitability to meet an aircraft's performance requirement. This statement is true for high aspect ratio wings where C_{L_α} and $C_{L\max}$ calculated numerically can accurately depict the wings behaviour between α_0 and $\alpha_{C_{L\max}}$. However, the non-linear nature of low $\mathcal{R}$ wings means the application of a linear C_{l_α} based model over the wings typical α would give an inaccurate prediction - especially at high angles of attack. These non-linear effects are the result of additional vortex lift acting normal to the wing due to high velocity tip vorticies. This phenomena allows low $\mathcal{R}$ wings to achieve a much higher $(C_L/C_D)_{\max}$ than that predicted by classical theories. However as C_{L_α} decreases and $\alpha_{(C_L/C_D)_{\max}}$ increases with $\mathcal{R}$ [5], the disadvantage of low $\mathcal{R}$ wings is a proportional decrease in C_{L_α} and $(C_L/C_D)_{\max}$ with $\mathcal{R}$. Therefore, while low $\mathcal{R}$ wings stall at higher angles of attack and are likely to outperform a higher $\mathcal{R}$ wing for a high range of α where $\alpha > \alpha_{(C_L/C_D)_{\max}}$, the high $\mathcal{R}$ wing will achieve a higher magnitude of C_L/C_D over $\alpha \leq \alpha_{(C_L/C_D)_{\max}}$.

Torres and Mueller [5] conducted wing tunnel tests of a range of wings with varying plan form and aspect ratio ($0.5 \leq \mathcal{R} \leq 2.0$) at Reynolds Numbers $R_N = 1 * 10^5$. This work was intended to provide reference to modelers and designers in the emerging field of Micro-AUV's, however these results are also conveniently applicable to low speed operation of the Slocum glider and the low aspect ratio wings of the low $\mathcal{R}$ vehicle. The airfoil of both Slocum glider wings is represented by the NACA 0006 section and as such carries the following properties as presented in [9]:

$$C_{l_\alpha} = 6.188/rad \tag{1}$$
$$C_{l\max} = 0.92 \tag{2}$$
$$\alpha_{C_{l\max}} = 9.0^o \tag{3}$$

Using these properties C_{L_α} can be approximated for a variety of wing plan forms using several theoretical methods - such as Prandtl's lifting line theory:

$$C_{L_\alpha} = \frac{C_{l_\alpha}}{1 + (C_{l_\alpha}/\pi \mathcal{R})(1+\tau)} \tag{4}$$

where $\tau = 0.4$ from [5], and $\mathcal{R} = 0.3155$ for the low $\mathcal{R}$ Slocum wing and $\mathcal{R} = 5.536$ for the standard high $\mathcal{R}$ wing. Another method is that presented by Lowry and Polharmus [3] which is proposed to better approximate the lift-curve slope of low $\mathcal{R}$ wings:

$$C_{L_\alpha} = \frac{2\pi \mathcal{R}}{2 + \sqrt{(\frac{\mathcal{R}^2}{\eta^2})(1 + \tan^2 \Lambda_{c/2}) + 4}} \tag{5}$$

where $\eta = C_{l_\alpha}/2\pi$, and $\Lambda_{c/2}$ is the sweep angle of the wing at midchord. Roskam [9] also proposed a similar form:

$$C_{L_\alpha} = \frac{2\pi \mathcal{R}}{2 + \sqrt{(\frac{\mathcal{R}^2\beta^2}{\kappa^2})(\frac{1+\tan^2 \Lambda_{c/2}}{\kappa^2}) + 4}} \tag{6}$$

where:

$$\beta = (1 - M^2)^{1/2} \tag{7}$$
$$\kappa = (C_{l_\alpha})_{atM}/(2\pi/\beta) \tag{8}$$

Finally Hoerner and Borst [10] propose that properties of thin rectangular plates with low $\mathcal{R}$ can be approximated by:

$$C_{L_\alpha} = \frac{1}{36.5/\mathcal{R} + 2AR} \tag{9}$$

Torres and Mueller [5] implemented the above methods, and comparative analysis with experimental results

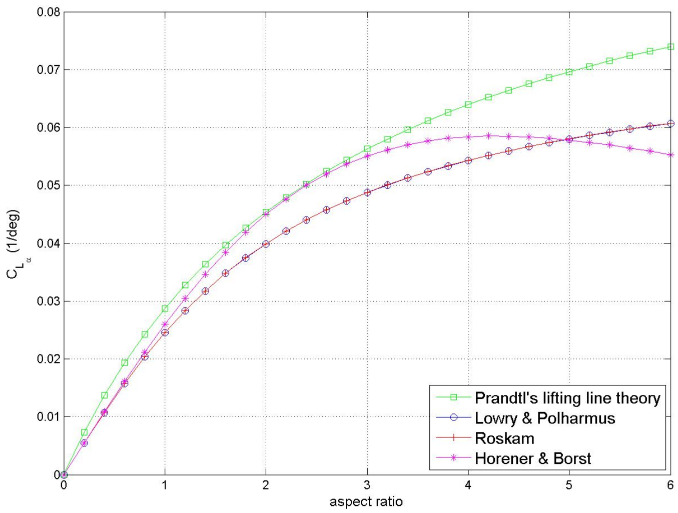

Fig. 3. Multiple predictions of the wing lift-curve slope of the low Æ plan form wing fitted to the Slocum glider

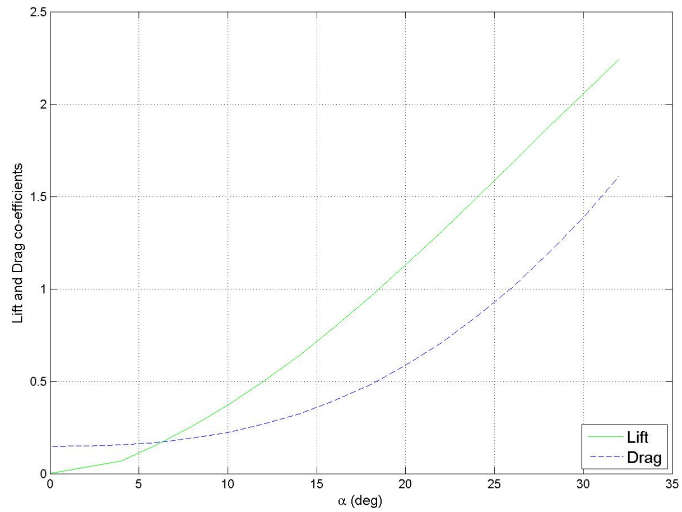

Fig. 4. Slocum Glider Body Alone Lift and Drag co-efficients

found Equations 4 and 9 (with $\tau = 0.4$) to give the best approximation of experimental data. Using these results a model of C_{L_α} for the low Æ wing plan form used on the Slocum Glider was developed for a range of aspect ratios (see Figure 3), which compared well with the data in the literature.

As is shown in Figure 3 the wing lift-curve slope of Æ ≈ 0.5 wings is significantly less than that of Æ ≈ 2.0 wings with the same plan form. This further illustrates that lower Æ wings have a lower magnitude $C_{L_{\max}}$ and reach this value at higher values of α. This is more prominent in the complete vehicle models and empirical results presented in the following section, where the introduction of low Æ wings is clearly shown to reduce $C_{L_{\max}}$ and $(C_L/C_D)_{\max}$ and shows $(C_L/C_D)_{\max}$ to occur at an α approximately 25% higher than the standard wings.

IV. Slocum Glider Model

In order to investigate any impact on the glider's propulsion efficiency from introducing low Æ wings it is necessary to derive the hydrodynamic parameters C_L and C_D for each vehicle and analyse the lift-to-drag ratio (C_L/C_D) of each glider variant. The derivation presented in this paper assumes that longitudinal and lateral-direction hydrodynamic coefficients are decoupled by the vehicle's symmetry. More specifically, it is assumed that longitudinal forces and moments depend only on longitudinal velocities and accelerations. Derivation of these parameters used a combination of inviscid flow and two-dimensional boundary layer flow theory's, as well as semi-empirical parametric methods from the literature. The NACA0006 airfoil section was chosen to represent the airfoil of both the standard and low Æ wings as it closely approximates the flat-plate like profile.

A. Body Alone

This section presents the predicted performance of the Slocum Glider's body section using the method prescribed by Fidler [11]. This method allows for the calculation of both axial flow (parallel to the body) and cross flow (normal to the body) for torpedo shaped bodies with the geometric properties of an ellipsoidal nose, cylindrical body, and conical base. This method employs potential flow theory for the linear components and a cross flow drag analogy for the non-linear components and has been shown in the literature to accurately approximate the body alone C_{L_b} and C_{D_b} up to angles of attack ≈ 25 with the assistance of empirical data [11]. The body alone normal co-efficient can be determined by:

$$C_{N_b} = a_1\alpha + a_2\alpha^2 \tag{10}$$

Where a_1 and a_2 represent the linear and non-linear components respectively. The non-linear component is caused by a lee-side vortex wake forming at $\alpha > 6$ at which point C_{N_b} becomes non-linear, Fidler [11] describes the axial flow and base drag components as remaining linear through $\alpha > 15$. The resulting C_{L_b} and C_{D_b} components of the standard Slocum Glider body alone are shown in Figure 4.

With the body operating in $R_N \approx 3 * 10^5$ this model assumes laminar incompressible flow over the area of the body exposed to oncoming flow.

B. Wings Alone

As discussed earlier the two variants of the Slocum glider interested in this research are distinguished by different wing plan forms and aspect ratios. The first is the standard Æ $= 5.536$ swept back wings where $\lambda_{c/4} = 45^o$. The non-standard or low Æ wings also have $\lambda_{c/4} = 45^o$ but with Æ $= 0.3155$ and would generally be considered as being in the range of extremely low aspect ratio. The typical relevance of classical aerodynamic theories extends down to $Æ \approx 5.0$ [7] therefore the standard wings can be modelled using Slender Wing Theory and Prandtl's Lifting Line theory, at least for what one would expect to be a relatively linear $C_{l_{\alpha_0}} \rightarrow C_{l_{\alpha_{\max}}}$. The final model of the standard wings also incorporated empirical data from [12] which contained wind tunnel data at the appropriate Reynolds Number of a wing with comparable plan form, tapper ratio and swept back angle as the wings of the standard Slocum glider.

The above mentioned methods cannot be readily applied to low $Æ$ wings as they do not predict the additional non-linear characteristics these wings have been shown to exhibit in the literature. The non-linear component is due to additional tip vortices generated by low $Æ$ wings which increases flow velocity behind the lifting surface, increasing the pressure gradient over the wing and ultimately manifesting as a additional lifting force acting in a direction normal to the wing. This is the basis of Polharmus' [13] leading-edge-suction analogy which predicts the additional vortex lift acting on low $Æ$ delta wings, as shown in Equation 11. The potential lift component is influenced by aspect ratio, leading edge shape, and sweep angle, while the vortex lift component increases linearly with angle of attack and is approximately equal to π [5].

$$C_L = K_p \sin\alpha \cos^2\alpha + K_v \cos\alpha \sin^2\alpha \quad (11)$$

where: K_p is the potential lift coefficient and K_v is the vortex lift coefficient.

Polharmus' leading edge suction analogy was later extended by Lamar [4] to include a side-edge suction force which also acts normal to the wing.

Bartlett and Vidal [14] developed the non-linear equation shown in Equation 12 which allows the contributions due to plan form, wing thickness and edge shape to be included through the cross flow term C_{D_C}.

$$C_{L\alpha} = C_{L\alpha,0}\alpha + C_{D_c}\alpha^2 \quad (12)$$

Fidler [11] describes a method to calculate the wing normal-force coefficient (C_{N_w}) based again on non-linear cross flow drag analogy which is very similar to that proposed by Bartlett and Vidal. Fidler's method (see Equation 13) shows excellent correlation with empirical results in the literature, where $a_1 = C_{N_\alpha} = \pi/2$ for $Æ \leq 1.0$ and a_2 is empirically derived.

$$C_{N_w} = a_1\alpha + a_2\alpha^2 \quad (13)$$

The research conducted by these authors and others has resulted in the publication of several non-linear equations which have been shown in the literature to

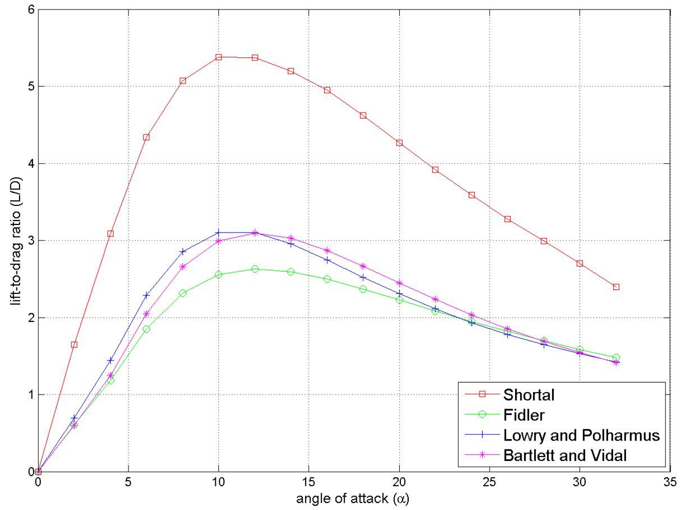

Fig. 5. Model of Slocum Glider with standard and low $Æ$ wings at $R_N \approx 3 * 10^5$. The Shortal model predicts the performance of the standard glider, all others predict the modified glider's performance

accurately predict the vortex lift of low $Æ$ wings, however their accuracy is heavily reliant on the availability of applicable empirically derived mathematical constants. Fortunately [5], [15], and [11] conducted experiments on several low aspect ratio wings with comparable plan form, aspect ratio, thickness and at similar Reynolds Numbers to that of the low $Æ$ wings designed for the Slocum glider. The experimental results presented by these authors provided the numerical constants required to utilize Equations 11 through 13 and develop predictions for the performance of the low $Æ$ glider.

Similarly, a semi-empirical model was derived for the standard Slocum glider using the experimental results of Shortal [12], who reported the lift and drag co-efficients for a wing highly representative of that of the standard glider.

The resulting vehicle model is shown in Figure 5 in terms of (C_L/C_D) for both the standard and low $Æ$ Slocum Glider.

The induced drag component of the vehicle models is calculated using Prandtl's lifting line theory, which takes the form of Equation 14 below:

$$C_D = C_{D_0} + KC_L^2 \quad (14)$$

where:

$$C_{D_0} = C_f \quad (15)$$

$$K = \frac{1}{\pi e Æ} \quad (16)$$

The value of K in Equation 14 was taken from empirical data in the literature.

C. Discussion of Modelling Results

From the vehicle model show in Figure 5 it is apparent that the low $Æ$ wings are predicted to introduce a signif-

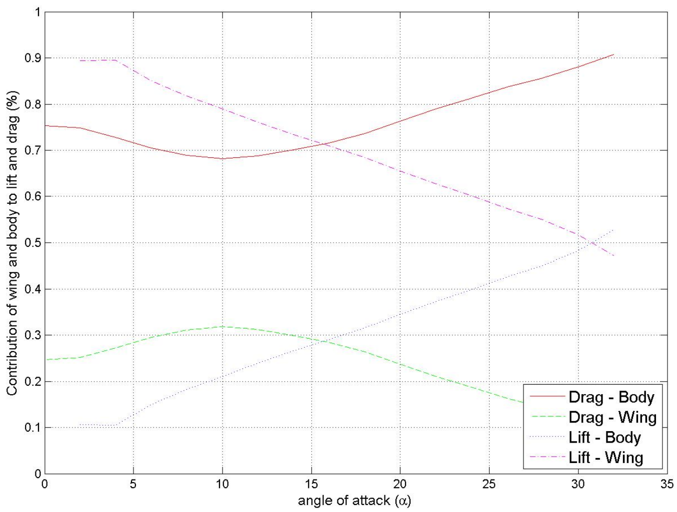

Fig. 6. Lift and drag contributions of vehicle components in model of standard Slocum Glider

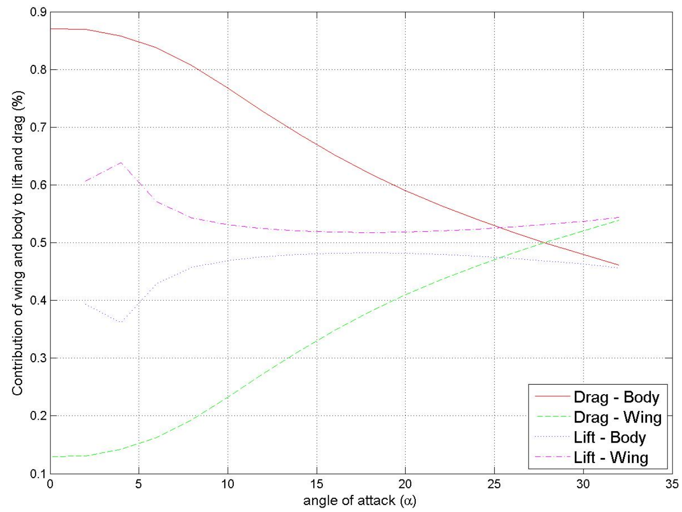

Fig. 7. Lift and drag contributions of vehicle components in model of low Æ Slocum Glider

icant performance degradation - which is consistent with the authors intuitive preliminary prediction. Figure 5 shows that all the low Æ vehicle models are highly correlated, and for further analysis the Barlett and Vidal model was chosen as the representative for performance of all the low Æ glider models. In comparison to the standard vehicle model, the low Æ model predicts a reduction in the magnitude of $(C_L/C_D)_{\max}$ and an increase in the α at which it occurs. The models also predict the rate of attenuation of C_L/C_D at $\alpha > \alpha_{(C_L/C_D)_{\max}}$ to be less for the low Æ glider than that of the standard glider. These two observations are supported by the literature of low Æ aerodynamics as described in section III.

The variation shown in the modelling results also predicts that the majority of each vehicle's lift to come from lift acting on the wings. To better understand the contributions of each wing design on C_L/C_D of the respective vehicle model further investigation into these contributions is shown in Figures 6 and 7. For illustrative purposes these results assume the body and wing apply the total force on the vehicle. The results show a clear prediction of performance degradation with the standard wings contributing between 89% and 47% of the total lifting force, where as the low Æ wings only contribute between 63% and 52% when mated with the same vehicle body. The model shown in Figure 7 is the Bartlett and Vidal model used here as the most representative of the three low Æ vehicle models.

V. Empirical Results and Discussion

The following empirical results were recorded during field trials is Tasmania's Lake St Clair - an inland glacial lake with a relatively benign underwater environment. Multiple mission were conducted over two days using the both the standard and low Æ version of the Slocum glider to transit identical paths with a saw-tooth trajec-

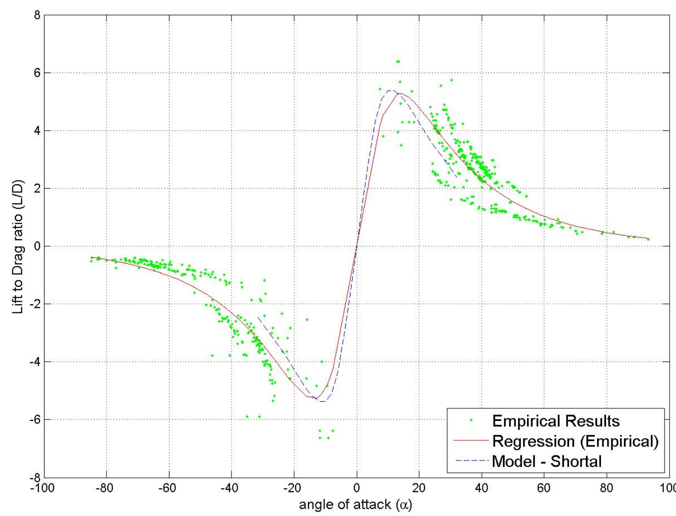

Fig. 8. Lift-to-Drag ratio of standard Slocum glider derived from empirical results, and corresponding vehicle model

tory between depths of 3 and 27 meters. The vehicles navigational, trim, and pressure sensors were recorded and used to produce the following set of experimental results. As it is not possible to determine the individual components of C_L and C_D from this trials data, the vehicles performance is presented in terms of total lift and drag forces and the ratio L/D. The empirical results as well as those from least squares optimized non-linear regression are shown for the standard and low Æ glider in Figures 8 and 9 respectively. Also included are the corresponding vehicle models for comparison.

The first, and perhaps the most surprising of these results is the overall lift-to-drag ratio achieved by each vehicle (based on the vertical and lateral distances travelled) which showed the low Æ glider to achieve a 5.3% higher L/D, which translates into 5.3% further lateral

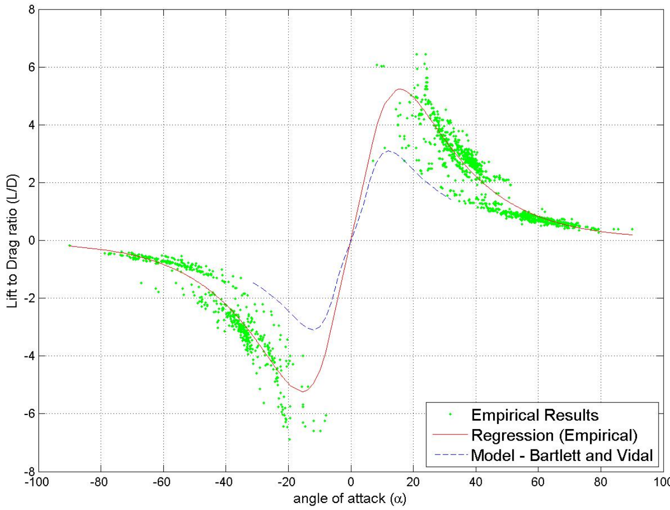

Fig. 9. Lift-to-Drag ratio of low Æ glider derived from empirical results, and corresponding vehicle model

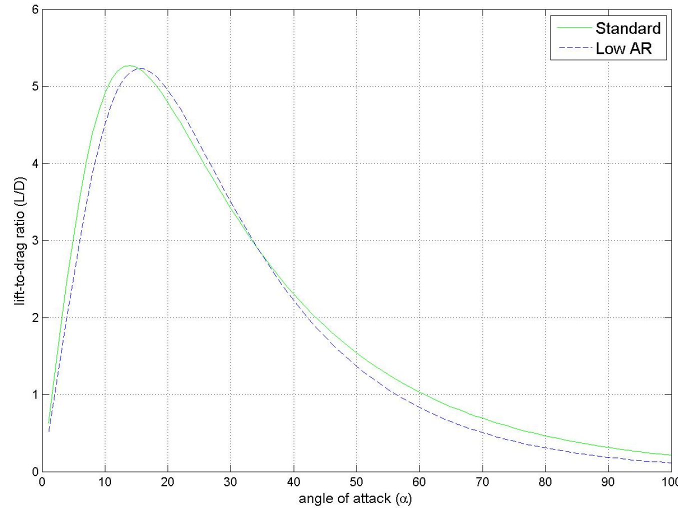

Fig. 10. Regression analysis of lift-to-drag ratio of standard and low Æ gliders derived from empirical results

distance travelled for the same verticle distance. This result contradicts the authors intuitive prediction and that of the low Æ vehicle models presented in Figure 5. The Shortal model and empirical data of the standard glider are highly correlated, which is not surprising as the standard glider has a customary profile and plan form and was modelled from traditional aerodynamic theories. However, the model of low Æ glider is significantly outperformed by the corresponding empirical results over the entire range of α. This may indicate that in practice the wings do not actually contribute as much as expected to the overall lift of the vehicle - and further indicating that the model of the body is inadequate. Alternatively the low Æ wings may be producing additional vortices over the vehicle body resulting in further vortex lift which was not included in the vehicle model.

The empirical results in Figure 10 show that both versions of the glider achieved similar L/D over the same range of angles of attack. While the low Æ glider has achieved significantly greater lift than expected, the same characteristics of the vehicle models are present; the low Æ glider achieved a lower magnitude $(L/D)_{\max}$ and did so at a higher angles of attack (approximately 15% higher) than that of the standard glider. This behaviour is consistent with the vehicle models and the literature, as is the period $15^o \leq \alpha \leq 34^o$ where the low Æ glider has a higher magnitude L/D (with a maximum 4% better L/D at $\alpha = 24^o$), representing less attenuation in lift-to-drag ratio for $\alpha > \alpha_{(L/D)_{\max}}$. However this condition inverts for $\alpha > 34^o$ where the standard Æ glider has a higher magnitude lift-to-drag ratio. This is contradictory to the literature which suggests that if two wings of different Æ had similar magnitude $(L/D)_{\max}$ then the lower Æ wing should continue to outperform the other for $\alpha > \alpha_{(L/D)_{\max}}$. However, technically the literature does not extend to such a large range of α, where any wing or vehicle would be deep in a stall condition and experiencing additional hydrodynamic effects. Traditional theories do not account for these effects occurring at such high α, and L/D results of wing tunnel tests are typically not reported at such high angles of attack because at this stage any vehicle would be operating far below $(L/D)_{\max}$.

Perhaps the most enlightening data is that of Figure 11 which shows the frequency of α during each glider's mission. This data shows that both gliders are operating at angles of attack much greater than that for the best lift-to-drag ratio for the majority of the mission time, and therefore are not yielding optimal L/D. The most common range of α for both gliders is between 20^o - 50^o, which heavily corresponds with the α range between 15^o - 34^o where the lower Æ glider was shown to marginally outperform the standard glider.

The asymmetry of the data in Figure 11 also suggests that for both gliders the control system is more capable of controlling the pitch angle in one range of α than the other - which may be a due to the asymmetry of the vehicle itself. Furthermore the greater frequency of α between 50^o - 70^o for the low Æ glider suggests the control systems ability to control pitch angle is slightly diminished by the hydrodynamic effects introduced by the low Æ wings.

VI. Conclusion

The field trial results presented in this paper show that a Slocum Glider fitted with extremely low aspect ratio wings was able to achieve a 5.3% performance increase over the standard vehicle. This is contradictory to the authors intuitive expectation, and the vehicle models, which predicted the lower aspect ratio wings to have a significant detrimental impact on performance. The authors hypothesize that this unexpected performance

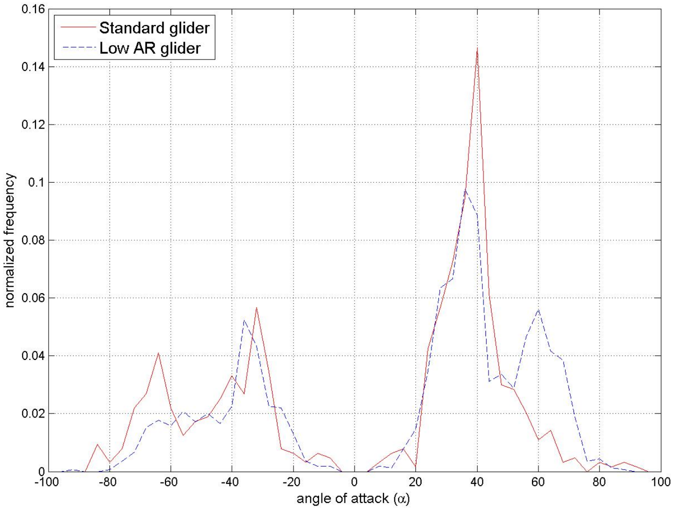

Fig. 11. Normalized histogram of α frequency experienced by both the standard and low Æ glider in field trials

is due to hydrodynamic effects contributing higher than anticipated additional lift. These effects could be caused by iteractions between the low Æ wings and the vehicles body producing high velocity vorticies over the wing and body uppper surfaces. This additional lift allows the modified glider to achieve a similar performance to the standard glider over the same range of angles of attack, and marginally superior performance for angles of attack between 15^o - 34^o. This range of superior performance corresponds with the range 20^o - 50^o where each glider spends the majority of its mission time.

These high angles of attack mean each glider is operating well outside the range for optimal flight performance. The authors further hypothesize that the control system of both vehicles performs sub-optimally in the shallow water environment in which field trials were conducted, resulting in both vehicles achieving comparative performance whilst both operating below their maximum lift-to-drag ratio.

The vehicles control system governs the pitch control of the vehicle and progressively adjusts the angle of attack during the saw-tooth climb-descent cycle. It is assumed that in deep water environments, the control system would stabilise the angle of attack, presumably around a value close to the maximum lift to drag ratio, and would thereby improve the relative performance of the standard glider. Therefore it is predicted that operating each vehicle in deeper water, where the control system can more readily reach a steady state, would show a greater separation in the performance results between vehicles. However, in shallow water the Slocum glider's control system is unable to maintain efficient angles of attack, and the performance impact of introducing low aspect ratio wings is insignificant.

VII. Acknowledgements

The authors would like to thank their colleagues James Gourley, Roger Neill, Andrew Tynan, David Liebing, Max Coxhead, Paul Dixon, John Barber and Phil Jackson from the Defence Science and Technology Organisation for their assistance in field trials and for their ongoing support and guidance. The authors would also like to thank Clayton Jones and Philip Collins from Teledyne Webb Research for their continued collaboration with DSTO.

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