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STUDY ON THE EFFECT OF WING GEOMETRY ON UNDERWATER GLIDER HYDRODYNAMICS

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ABSTRACT

The United States Navy have outlined an unmanned underwater vehicle master plan, which includes nine distinct capabilities for these vehicles, some of which may be suitable for underwater gliders. An underwater glider is a type of unmanned underwater vehicle that has a unique concept of propulsion using a combination of buoyancy driven engine and wings. In this paper, four different wing geometries; swept wing, swept back wing, elliptical wing and delta wing, are investigated to determine a suitable wing geometry for a given mission type. The computational fluid dynamic software, ANSYS FLUENT, was used to determine the glider hydrodynamics at different angles of attack. The delta wing has the highest drag followed by the elliptical, swept and swept back wing. Similarly, the delta wing had the highest lift; followed by the elliptical, swept and swept back wing. Underwater gliders are deemed capable of six distinct capabilities. Appropriate wing types were determined for a given mission based on three glide characteristics, which are stability/manoeuvrability, speed and endurance.

Keywords: underwater glider, wing geometry, hydrodynamics.

INTRODUCTION

Underwater gliders are buoyancy-propelled, fixed-wing unmanned vehicles with attitude controlled completely, or in part, by means of internal mass redistribution [1, 2]. They are capable of undergoing long duration mission, have good operational flexibility as well as low cost of operation [1, 3, 4]. The most common task of these gliders is to carry out deep sea exploration and ocean observation [5, 6]. The United States of America Department of Navy have outlined an unmanned underwater vehicle master plan which includes 9 distinct capabilities for these vehicles, some of which may be suitable for underwater gliders. In this work, the effects of four different wing geometries; swept wing, swept back wing, elliptical wing and delta wing, on the hydrodynamics and behavior of these gliders, when subjected to different angle of attack, are investigated to determine the suitable wing geometry for a given mission type.

The seminal work by Graver, Bachmater and [1, 2] on underwater gliders has spurred their development. Using existing glide and wind tunnel data, Graver simulated the glide of the WE01 Slocum glider using Computational Fluid Dynamic (CFD) method [3]. The CFD is powerful tool to investigate hydrodynamic characteristics of marine vehicles.

CFD SIMULATION SET-UP

For each wing geometry, five models were developed for five different angles of attack, by varying the angle of attack from -20˚ to 20˚. The glider is positioned inside a 3.5 m x 3.5 m x 7.5 m fluid domain, which will act as the boundary condition or area of flow for the fluid as shown in Figure-1.

A horizontal velocity of 0.3 m/s from the inlet boundary towards the outlet boundary with a Spalart-Allmaras turbulence model, similar to Ting's [4] simulation, was used. The 3D Spallart Allmaras turbulence model was used as this one equation model is sufficient to solve most aerodynamic and hydrodynamic problems [5]. To ensure the convergence, 600 iterations were performed. Graver's [6] data was used to validate the simulation results.

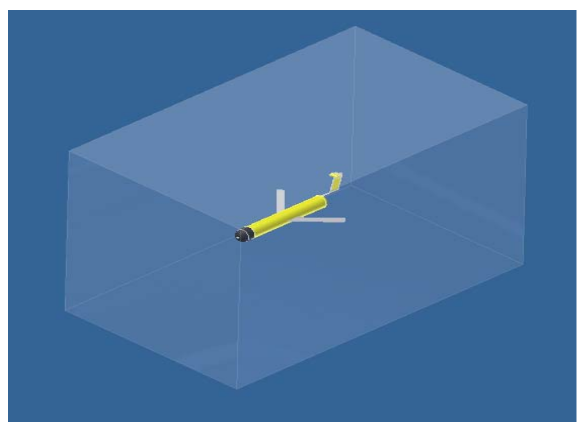

Figure-1. SLOCUM glider position in the middle of the domain.

RESULT AND DISCUSSIONS

The drag coefficient (C_d) for angles of attack from -2º to +2º of the Slocum glider (see Figure-2) in one degree increments has been compared with Graver's experimental data[6]. The results show a similar parabolic function of the drag coefficient as in Graver's parameter identification analysis, with an error of approximately 13%.

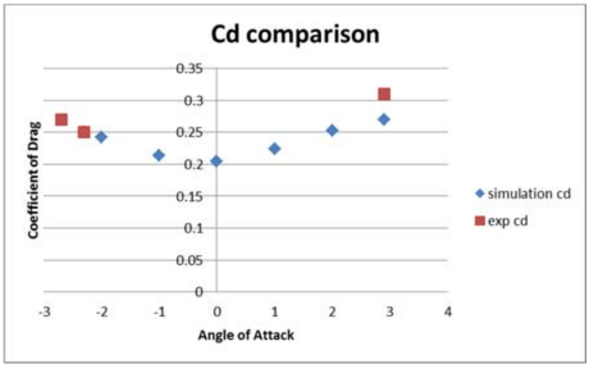

Figure-2. Cd comparison between simulation (blue) and experimental (red).

EFFECT OF WING DESIGN ON DRAG COEFFICIENT AND LIFT COEFFICIENT AT DIFFERENT ANGLES OF ATTACK

The configurations of swept wings are given in Figure-3. The low drag in the swept back wing geometry will allow achieving high speed manoeuvrability of glider. For any given angle of attack, the highest drag coefficient is produced by the delta wing, followed by the elliptical, swept and swept back wing as shown in Figure-5.

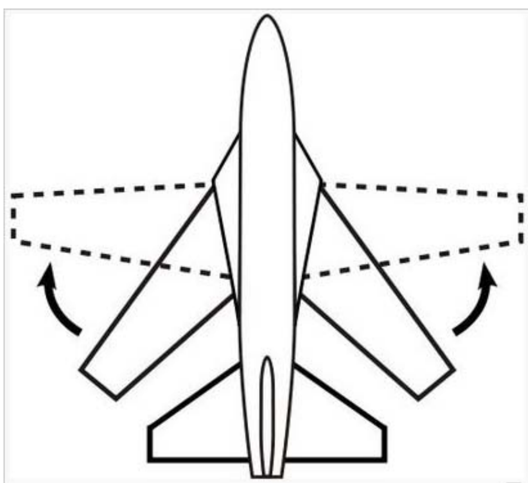

Figure-3. Variable sweep wing.

The lift force is perpendicular to the velocity vector and the Drag force is parallel to the velocity vector of glider as shown in Figure-4.

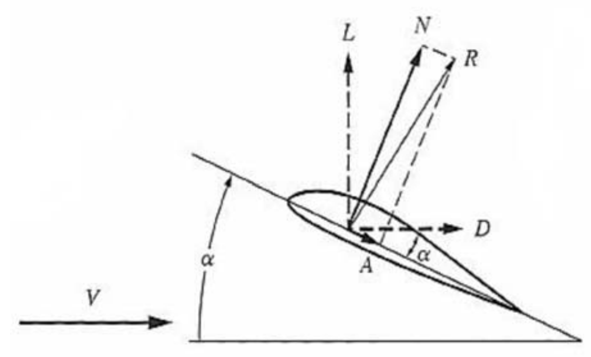

Figure-4. Components of forces on wings air-foil [7].

The lift force of delta wings increases up to 71% with an increase of 35% in drag force as compare to the Slocum glider. The difference in drag coefficient is due to variation in skin drag between the wing geometries. The delta wing has the largest wing area, producing additional drag on the glider body. This drag force is directly analogues to the velocity and power source of glider. The power source is requiring maintaining the desire velocity of glider as the drag force increase.

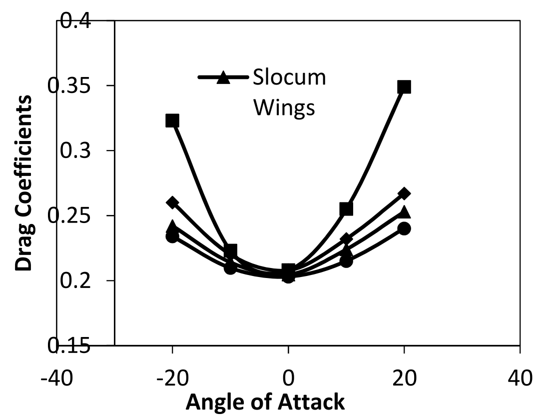

Figure-5. Coefficient of drag against angle of attack.

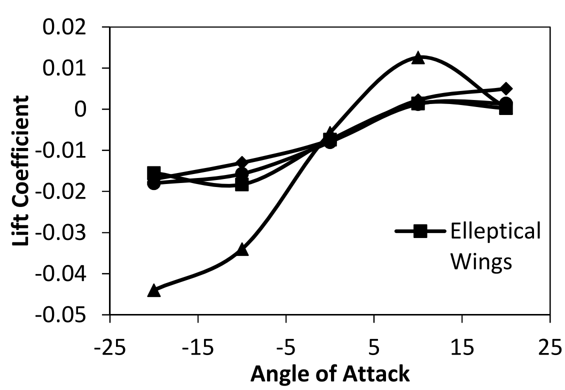

Figure-6. Coefficient of lift against angle of attack.

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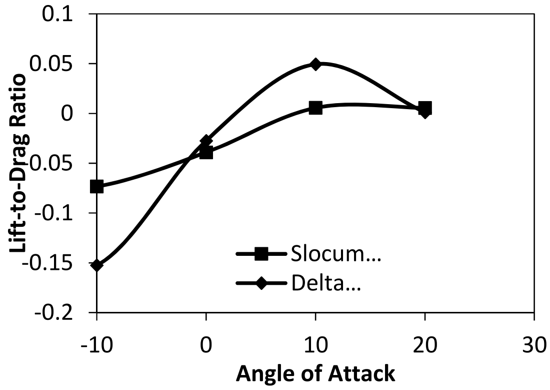

Figure-7. Lift-to-drag ratio against angle of attack.

In addition, the horizontal and sink rate of glider has direct relation with the lift-to-drag ratio of glider [8]. The relationship between lift to drag ratio is:

$$\frac{L}{D} = \frac{V_x}{V_y}$$

Here L/D is lift-to-drag ratio, V_x is horizontal velocity and V_y is sink rate of glider.

The delta wing glider has more lift-to-drag coefficients as compare to Slocum glider as shown in Figure-7. This shows that the delta wing glider is more suitable for shallow water with high speed as compare to the Slocum glider.

Current the blend-body shape delta wing gliders are used for shallow water under the USA navy [9, 10] as shown in Figure-8.

Figure-8. XRAY glider (USA Navy).

EFFECT OF WING DESIGN ON DRAG FORCE AND LIFT FORCE

Since the delta wing geometry has the highest drag coefficient, naturally it has the highest drag force. As angle of attack increases, the amplitude of the drag force rises as pressure drag increases due to wake turbulence from the larger angle of attack. Therefore, drag is greater for a wing with a higher drag coefficient with minimal difference observed at zero angle of attack.

Similarly, for lift coefficient and the lift force, the large area of the wing allows for lower fluid flow under the wing, resulting in pressure increase under the wing (lift). Thus, at greater angle of attack, the larger wing will have greater lift compared to other wing geometry.

Table-1. Lift and drag forces for different wing geometry.

Lift Force (N)					
	-20	-10	0	10	20
Slocum	-0.826	-0.705	-0.355	0.057	0.659
Swept Back	-0.776	-0.56	-0.34	-0.098	-0.244
Elleptical	-0.696	-0.824	-0.334	0.064	-0.0116
Delta	-1.97	-1.543	-0.26	0.568	-0.019

Drag Force (N)					
	-20	-10	0	10	20
Slocum	10.87	9.64	9.19	10.08	11.35
Swept Back	10.51	9.42	9.12	9.66	10.74
Elleptical	11.68	9.9	9.38	10.44	11.98
Delta	14.53	10.001	9.36	11.48	15.67

Table-2. Wing geometry recommendation based on mission type.

Mission type	Recommended wing geometry	Remarks
Intelligence, surveillance and reconnaissance (ISR)	Swept wing geometry	Lowest drag, highest aspect ratio
Mine counter measures	Swept wing	Lowest drag
Anti-submarine warfare	Swept wing	Highest aspect ratio
Inspection/ Identification	-	UW glider not suitable for this operation
Oceanography	Swept wing	Lowest drag, high aspect ratio
Communication/ Navigation network Node	Elliptical wing	Low aspect ratio
Payload delivery	Swept back wing	Low drag, low aspect ratio
Information operations	-	UW glider not suitable for this operation
Time critical strike	-	UW glider not suitable for this operation

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MANOEUVRABILITY, SPEED AND ENDURANCE CRITERION

Before getting into the classification of mission type, a design criterion must be first established. The criteria suitable for the development of underwater glider are stability or maneuverability, speed and endurance. An underwater glider with external payload will also require stability in its motion to ensure the payload is not damaged or even worst, dropped before the destined point. To achieve this, the wing design and the overall glider design must have a low aspect ratio. The small aspect ratio allows for greater roll angular acceleration. If maximum speed is desired, then the design must produce the lowest value of coefficient of drag at the maximum glide speed at -34 degree glide path angle. For normal, electric-battery powered glider, the maximization of the energy translates to longer operational range. For this to happen, in terms of the design, the lowest drag design is preferable since it will allow the glider to glide with less resistance. Lowest drag coefficient alone is not enough since the glider need to move in vertical direction as well. In this case, a highest lift to drag ratio is required. Summary of different wings geometry and their relative possible application are given in Table-2 [11, 12].

CONCLUSIONS

An underwater glider with different wing geometry is subjected to different hydrodynamic forces. The wing geometry with the lowest aspect ratio has the highest amount of drag. Variations in the aspect ratio also effect the maneuverability of the glider with a lower wing aspect ratio able to produce higher angular acceleration thus, better maneuverability. Despite operating underwater at low speeds, the drag behavior of an underwater glider is quite similar to the drag behavior of an aircraft, although the magnitudes of the hydrodynamic and aerodynamic forces respectively are very different. The largest wing geometry, the delta wing, produces the largest lift force and the largest drag force compared to other wing geometry. The outcome of this study will be useful for the design of future underwater glider that is required to fulfil a given mission type. However, more research on the overall design of the glider can be made by studying the effect of NACA (National Advisory Committee for Aeronautics) airfoil designs, which could dramatically improve the lift and drag ratio of the glider.

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