CFD analysis and hydrodynamic improvement on hybrid buoyancy driven underwater glider for extended range capabilities

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ABSTRACT. *It is well known the high capability of underwater autonomous gliders for travelling long distances in ocean survey missions [1]. Despite the high endurance of such vehicles, there are important difficulties to control their trajectory in the desired direction in some specific cases. The most frequent situation appears when unexpected unfavorable external environmental conditions affect their dynamic capability. These external disturbances, consequence of marine currents, rotational dynamics, high turbulence or high density gradient areas, can make difficult or even preclude the possibility of conducting the desired navigation path. With the aim of providing more dynamic capacity to a buoyancy based propulsion vehicle, it has been proposed a dual buoyancy engine for application in the Alba 14 underwater glider [2]. This combined buoyancy system can provide improved maneuverability when external conditions would recommend additional thrust [3]. As continuation of previous works [4][5] several advances in the design of the underwater glider Alba-14 are presented in this paper[6][7]. The analysis presented has been mainly focused in identifying the hydrodynamic performance~~s~~ of the glider. The main goal is to extend the vehicle endurance and range. Simulations of the vehicle from CFD analysis using Ansys-Fluent® software at different angles of attack and velocities are presented (fig 1). Field experiments confirmed the ability of the vehicle to navigate at increased velocity than the standard ones although sacrificing its maximum range.*

Keywords*: Underwater Gliders, AUV, Low Cost Underwater Vehicle, Marine Robotics, Arduino.*

I INTRODUCTION

Since the first vision of Henry Stommel on underwater gliders as excellent systems for conducting extended ocean research [8], these vehicles have demonstrated their feasibility as high endurance ocean observation devices. Multiple experiments and deployments in the past [1] have confirmed their high suitability in applications where high persistence in the ocean environment is desirable [1]. Because their particular system of propulsion based in the variation of the vehicle buoyancy and in association with external wings conveniently orientated, underwater gliders can navigate long distances by using a reduced amount of energy. Despite these advantages, there is an important drawback related to this kind of propulsion that should be considered. Most popular today gliders have a small value of buoyancy variation capacity. For this reason, the maximum velocity that gliders can perform is necessarily very low (0.1-0.25 m/s). Being the usual variation in volume of near 200 cm^3 in normal operation, which represent 2 N around of maximum available force in most common commercial gliders [9][10][11]. This value represents a 0.4% of the total mass of the vehicles (50 Kg around). The low value of this buoyancy force together with the need of conducting saw-tooth trajectories (the second important drawback of these vehicles) limits their maneuverability [12]. Buoyancy based propulsion does not allow a pure glider vehicle to conduct horizontal navigation because the alternated buoyancy/diving pattern is directed towards gravity vector that is in vertical direction

limitation, several designs have been proposed which combine the advantages of gliders with the ability of propelled vehicles for conducting horizontal navigation and more controllable course [13][14]. These proposals have demonstrated their feasibility for specific applications [15].

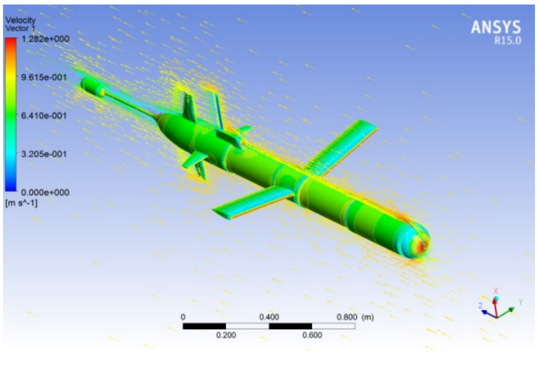


Fig. 1. Alba-14 flow velocity pattern at 1.0 m/s surge speed in the plane vertical plane with angle α=0. An hypoteticla electrical propulsion should deal with the important effect of drag associated to the external appendages frequent in gliders.

However, the propulsion efficiency in same conditions will be necessarily worse for a glider than the equivalent AUV due to the parasitic drag associated to the glider wings, which bigger than the usual tail fins in an AUV Fig. 1. This higher drag will reduce the features of the glider in propelled mode especially with respect maximum range and velocity.

This kind of hybrid propulsion, although very promising and interesting in specific applications [15], are not primarily intended to extend the range of the vehicles because the limitations on internal spaces for housing the dedicated set of batteries for the propeller subsystem. These complements are rather intended for adding to the vehicle the possibility of navigating in other mode than saw-tooth pattern when it is required for the mission. In addition, as an important drawback of these hybrid systems, it should be mentioned the fact that they add complexity and increase the possibility of unexpected failure. For exploring other ways of providing increased maneuvering capacity it has been implemented a dual buoyancy system in the Alba 14 glider [2][3]. With the aim of advance in the development and optimization of the low-cost Alba 14 glider, fluid dynamics simulations have been conducted for obtaining the vehicle hydrodynamic parameters and characteristics. First results and data from the analysis are presented in this paper, showing promising capabilities for obtaining an improvement in vehicle features. These augmented characteristics can be of great interest in cases when adverse external conditions are present in the area of survey.

II DUAL BUOYANCY CONCEPT FOR INCREASED FEATURES

The propulsion of the vehicle Alba-14 is based on a hybrid configuration combining two different fluid buoyancy engines based on gas and liquid. The oil type fluid component buoyancy engine is, as other similar and successful glider designs [1][2][3], based in the combination of external bladder and in/out transfer of hydraulic oil. The fluid volume is relocated from the internal reservoir to an external bladder by means of a reciprocating pump rated for the maximum operational depth (Fig. 2) of the vehicle; initially set to 120 m for the first prototype of the Alba-14. This action increases the vehicle volume and thus its buoyancy which, combined with an appropriate pose, produces a resultant component of the velocity in surge direction.

Because a mass of liquid is transferred from the internal reservoir to the bladder in other location, a mass displacement is produced in addition to the increase in buoyancy.

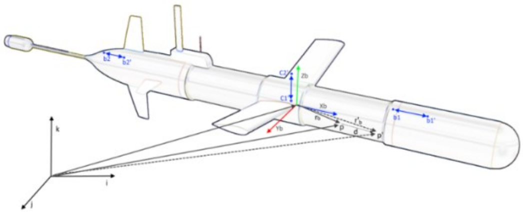


Fig. 2. Variable buoyancy subsystems (fore and aft, above in blue) and internal moving mass (below hull central section in black) with a generic framework of reference

These changes in mass distributions alter the value of net buoyancy and then, the relative position of the center of mass (CG) with respect the center of buoyancy (CB) and a change of the moment than should be compensated. For this reason, appropriate trimming operations by moving internal masses should be then carried out for adjusting the attitude of the vehicle in each transect.

An additional effect that can be observed from CFD analysis is the intensity of the wake inception backwards the vehicle during forward steady navigation (Fig. 3), will reduce the effect of the fluid of the boom and transducer as it is deduced from simulations. However, during maneuvering (sharp turn) adverse moment and advance drag will become more important since rear boom and sensor housing are less affected by this favorable wake effect. These changes in hydrodynamic efficiency should be considered in the model for the accuracy validation between the model and the real prototype.

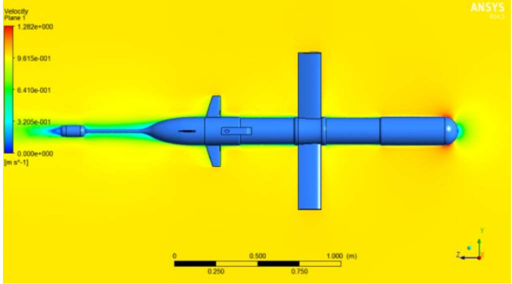


Fig. 3. Alba-14 flow velocity pattern at 1.0 m/s surge speed in the horizontal plane it can be appreciated the important wake effect at the aft zone of the vehicle

The internal mass moving system will be the main responsible of the attitude control in the longitudinal (X-Z) plane during ascending/descending legs in saw-tooth navigation pattern. Once the vehicle reached a stabilized pitch angle and desired speed, the effective flight attitude in combination with the ideal angle of attack in each case will produce an effective lift and drag effect. Additional adjustments should then be performed for optimizing the desired gliding path. Model simulations by CFD software Ansys-Fluent ® will provide a reference for the optimal attitude in each operational configuration. Lift force generated in the wings due to a small angle of attack will however lightly modify the path angle (Fig.6) due to upwards-downwards lift force component. In addition, drag force will affect to the maximum speed of the vehicle for each given conditions. The secondary gas based buoyancy engine is intended for boosting the vehicle in specific conditions or when it is necessary more thrust in specific stages of the mission.

Lift and drag forces for a given condition are derived from the following semi-empirical relations:

$$L = \frac{1}{2}\rho A_w C_L V^2 \qquad D = \frac{1}{2}\rho \mathrm{A} C_D V^2$$

Considering a value for the frontal projected area of the vehicle, A = 0.049 m^2 and wing reference area A_w= 0.104 m^2 , C_L and C_D are computed from CFD simulation fig. 7 at 0.5 m/s α=0º

Minimizing the value of the parameters A, A_w and $C_{L,D}$ will have as effect the increase of the velocity of the vehicle but for a given design these parameters are given and cannot be modified. For a fixed and specific vehicle shape and dimensions, only an increase in forces or changes in attitude can deal with the effective drag to obtaining a gain in velocity. For this reason, higher values on the net weight/buoyancy effect has been adopted as solution for keeping the functionality of the vehicle as well as the maximum diving velocity of around 0.8 m/s. This value of the velocity will nevertheless require the optimization of the hull and the shape of the wings, for reducing at maximum the drag of the vehicle (Fig. 4)

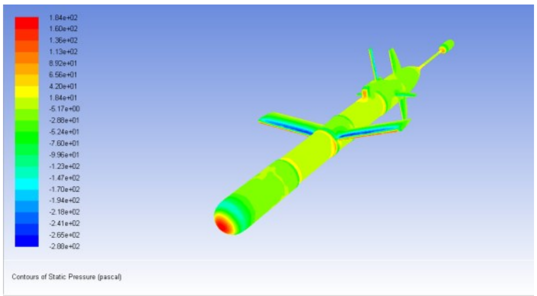
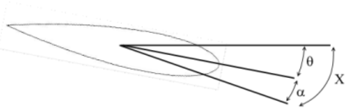


Fig. 4. Pressure distribution contour on the vehicle hull and wings. An important lift effect can be observed on the extrados of the wings. This effect will affect to the glide path angle due to the lift force generated as well to the surge velocity due to the drag from lift adverse force.

III CFD DRAG RESISTANCE ANALYSIS

As it can be observed from fig. 3 and fig. 4, an increase of 6.0 % in drag force with respect 0 angle of attack (red line), is obtained from the CFD analysis. This pattern of downward (upward) is more realistic since negative (positive) buoyancy produces a small angle between surge velocity $\vec{u}$ and X in the body frame reference (Fig. 5). Due the effect of lift produced by α≠0 and the drag associated to the lift effect, pitch attitude adjustments are necessary for obtaining the desired optimal gliding path angle χ These trimming procedures will be focused in keeping the optimal pose of the vehicle for the desired operative conditions and for optimizing the effect of lift in the wings (Fig. 6). Since velocity is not directly measured, only dead-reckoning measures based in the model behavior and the IMU data will be available. For this reason an accurate model based in the CFD analysis should be considered.



$$\alpha = \chi - \theta$$

Fig. 5. Angle of attack α in function of glide angle χ and pitch θ relationship in longitudinal plane

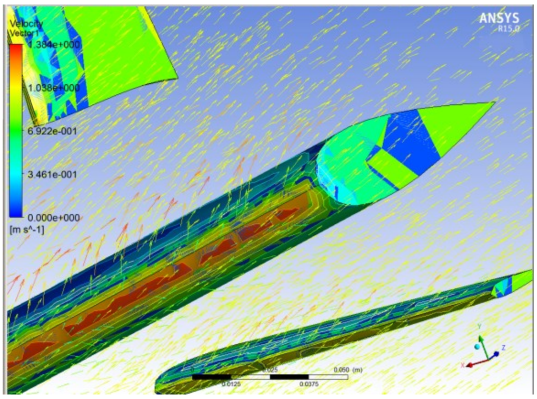


Fig. 6. Image taken from CFD simulation of wings and rear planes uncoupled from the hull showing the increase of pressure in the leading edge and velocity vector at 4º angle of attack.

As it has been previously mentioned, the multiple variable buoyancy system implemented in the Alba-14 vehicle is intended for allowing to adapt itself to a plethora of possible different external conditions. For this reason, optimizing the glide pattern in each upward-downward leg is essential to maximize the limited internal stored available energy.

Reduced the drag to lift effect seems to be of slight value of the lift force (L) associated to the low value of flow velocity on the wings. In addition there is a small effect of drag from lift effect DLift is, because the low values of α.

$$D_{Lift} = L \sin \alpha$$

Long term surveys conducted by gliders including different ocean areas will suffer from very different local conditions,(waves, traffic, currents, seafloor orography, etc.) and will require appropriate adaptation to each situation.

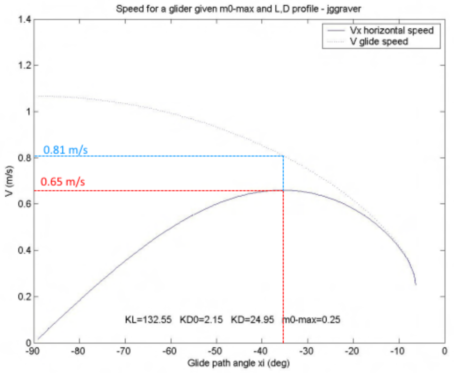


Fig. 7. Optimal glide angle for maximum effective horizontal velocity is obtained at 36º path [8].

As it is studied in previous works [8], a function that represent the horizontal sea-ride distance has a maximum for an angle of glide of 36º (Fig. 7). This angle should be considered as optimal glide for a given condition, and should be among the main goals when planning any route when the maximum distance travelled is paramount.

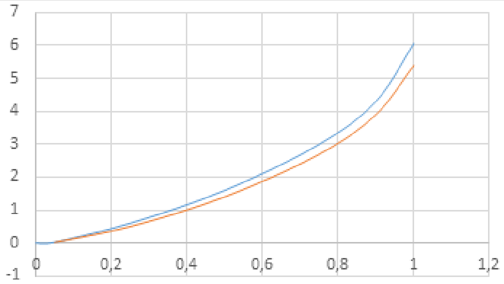


Fig. 8. The total drag resistance will increase as α increases due to increase in frontal area and Drag due to lift effect. In the graph below the effective drag force at 0º angle of attack (red) in steady glide flight and small α (blue). Velocity in m/s VS drag Force in N.

Combining different navigation configuration schemas, path angle adjustments and net buoyancy as a source of thrust will allow the vehicle to adjust itself to the most appropriate buoyancy system in each condition. Adjusting procedures of pose control will be oriented to reduce the additional drag generated by the effect of angle of attack and lift effect (Fig. 8).

Different operative settings for the Alba-14 vehicle are considered (red shadowed areas) depending on the requirements in the ratio between horizontal to vertical speed, three operative envelope areas proposed (Fig. 9). Maximizing the range of the vehicle will require minimizing the downward component of the velocity and thus, reducing the path angle (zone 1).

This configuration of glide because the small slope, will require an additional value of the buoyancy and probably a modification on the configuration of both wings. The goal in this case will be maximizing the range saving the minimum of potential energy on each leg (heave velocity, y-axis)

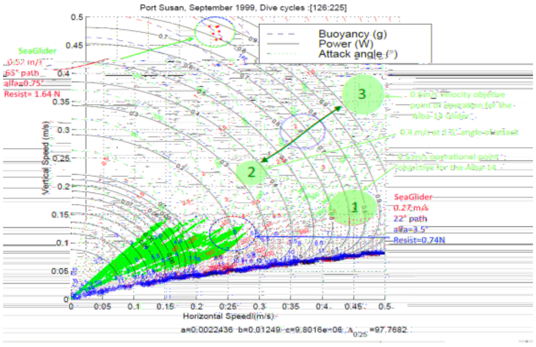


Fig. 9. Diagram applied in to several dives cycles of the Sea-Glider that can be extrapolated to the Alba-14 vehicle and to any kind of underwater glider [16].

Adverse external conditions will require more power for providing to the vehicle more thrust specially in the upper layer of the water column [3].

This behavior is reflected in the (Fig. 9), in the operational zones 2 and 3. In this gliding mode the vehicle will switch between two states depending on the external constraints and sailing requirements.

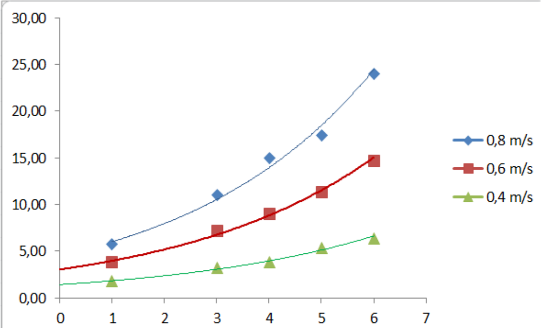


Fig. 10. Drag resistance of the Alba-14 (y-axis force in N) at different glide speed values and angle of attack (x-axis angle of attack)

IV CONCLUSIONS

An analysis of the drag resistance and expected features applied in the hybrid glider Alba-14 SGL has been presented. CFD analysis shows that providing an augmented buoyancy capacity gives to an increase on the velocity of gliding. This augmentation in the dynamic capacity of the vehicle can help to deal with external adverse conditions by using the proposed combined buoyancy, allowing the vehicle to dive up to speeds of near 0.8 m/s which will improve the capacity of other pure glide commercial gliders (Fig 10). First CFD analysis presented in this paper confirm the experimental results (Fig. 11) and will be useful for obtaining further hydrodynamic parameters of the vehicle. These data in combinations with real field information are expected to be very useful for obtaining an accurate mathematical model of the vehicle and applying to the planning of future long term operations at sea specially in cases when multiple configuration of heterogeneous vehicles with self-planning capabilities with a limited supervision from external sources increasing the autonomy of the system [17].

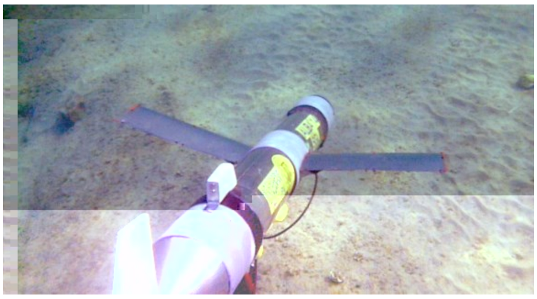


Fig 11, Real field test of the Alba-14 glider which showed its ability to control a stable path and glide angle by adjusting the roll and pitch parameters.

V FURTHER WORK

Further work will include carrying out additional CFD analysis with different wing configurations, assessing different profiles and dimensions on both, planes and hull of the vehicle. Further improvements and variations applied to the external appendages (aft mast and underwater communications transducer upper housing) will be considered. It is intended to conduct real tests at sea for providing feedback about the systems and solutions implemented in the proposed design for optimizing purposes.

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