CONTROL SURFACE AND ACTUATOR DESIGN FOR A LOW DRAG, LAMINAR FLOW AUV

S L Merry[*], M J Large[**], T J Whitten[**], M R Wilkinson[**] and R J Babb[***]

[*]Institute of Sound and Vibration Research
University of Southampton
Southampton SO17 1BJ, UK

[**]Department of Aeronautics and Astronautics
University of Southampton
Southampton SO17 1BJ, UK

[***]Ocean Technology Division
Southampton Oceanography Centre
Empress Dock
Southampton SO14 3ZH, UK

Abstract

The design process for the control surfaces and actuators of the long distance AUV DOLPHIN (UK "Autosub" project) is described. The main design criteria are low drag, reliability, robustness and energy-efficiency. The aerodynamic characteristics of four NACA foil sections and various stabiliser/moveable fin geometries are compared, in order to reach the final design, which incorporates a NACA 66-009 wing section with a partial span trailing edge flap. The actuator is located in a wing-tip pod, which also houses the sensors for oceanographic data logging. Preliminary analysis of wind tunnel tests on a full-scale model of the control surfaces confirms that the lift force required to achieve the specified manoeuvrability for DOLPHIN is easily generated. Measured drag data is lower than expected and this requires further analysis.

1. INTRODUCTION

Widespread public concern about the increasing greenhouse effect of the world's atmosphere and consequent global warming has led to a requirement for improved climate forecasting. In order to meet that requirement, temporal and spatial monitoring of the world's oceans on a three-dimensional, global scale is needed, to validate mathematical models of the ocean circulations. These models can then be used at higher confidence levels to predict climate change.

Autonomous underwater vehicles (AUVs) has been proposed as cost-effective and efficient platforms for oceanographic data collection [1]. The potential benefits of this concept are such that the Natural Environmental Research Council (NERC) in the UK has funded a Community Research Project for technological development of AUVs, named Autosub. The project is hosted by the Ocean Technology Division of the new Southampton Oceanography Centre (formerly part of the Institute of Oceanographic Sciences, Deacon Laboratory).

One of the long-term goals of the project is to produce a vehicle which will track across the ocean basins, sampling continuously. This Deep Ocean Long Path Hydrographic Instrument (DOLPHIN) will carry out profiles from the surface to the seabed, surfacing every 30 km to fix its position by GPS satellite and to return data to shore stations.

In order to meet the specified trans-oceanic range of 7000 km, within the limitations of currently available power storage systems, an energy-efficient hull form is required for the DOLPHIN. Research in the 1960s and 1970s identified the inherently low drag characteristics of natural laminar flow shapes [2, 3] and model tests on a laminar flow design by Huggins and Packwood [4] confirmed a drag coefficient of 0.0061 which is 75% lower than the drag of an equivalent torpedo-shaped hull-form at the same Reynolds No., in a controlled, low turbulence environment.

The final design of the DOLPHIN hull based on the Huggins and Packwood shape is shown in Figure 1. The overall length is 6.0 m, with a displaced volume of 4.4 m^3.

Figure 1. Hull Form of the AUV DOLPHIN

Laminar flow will be maintained for 70% of the length at the cruise velocity of 2.5 m/s. Free ascent trials of a half-scale model in the open ocean indicated a 50% reduction in drag as compared with a torpedo-shaped hull of the same internal volume, under realistic operating conditions [5].

Various sub-systems of the vehicle, such as power storage, buoyancy control, mission management and propulsion, are currently under development. The present paper describes the design and testing of control surfaces and actuators for DOLPHIN.

2. DESIGN BRIEF

For its mission of oceanographic data logging through the water column, DOLPHIN will follow a saw-tooth path profile as it traverses the ocean [Figure 2]. The submersible will descend from the surface at an angle of about 45 , continuously monitoring data such as temperature and salinity as a function of depth. As it nears the ocean floor, the vehicle attitude will change, in order to ascend vertically to the surface, where the data will be off-loaded via satellite. Before repeating the cycle, a GPS position fix will be obtained.

Figure 2. Trans-Oceanic Path Profile of the AUV DOLPHIN

The path profile described above, which necessitates only gentle alterations from a straight-line course, defines the specifications for the control surfaces of providing a minimum turn radius of 100 m.

The main design consideration for the control system of DOLPHIN is energy-efficiency. The selected foil geometry must have low drag; the actuator mechanism and control strategy must be designed to minimise energy consumption. Other mechanical factors to be addressed include operation at high pressure (maximum operating depth 6000 m), long term reliability and resistance to mishandling during launch and recovery.

The control surface geometry should also incorporate a location for oceanographic sensors, such as a CTD measurement device.

3. CONTROL SURFACE DESIGN

3.1 *Selection of the Aerofoil Section*

The aerodynamic characteristics of four symmetrical NACA foils, the basic 0006 and 0009 and the laminar flow 66-006 and 66-009, were compared in order to select the most efficient section for the control surfaces [6]. A graphical comparison is presented in Figure 3 (stall angle versus Reynolds No.), Figure 4 (minimum drag coefficient versus Reynolds No.), and Figure 5 (maximum lift coefficient versus Reynolds No.).

Figure 3. Stall Angle versus Reynolds No. for Candidate Foil Sections

Figure 4. Minimum Drag Coefficient versus Reynolds No. for Candidate Foil Sections

Figure 5. Maximum Lift Coefficient versus Reynolds No. for Candidate Foil Sections

The 0009 foil is clearly superior in terms of stall angle and maximum lift coefficient; however, it also exhibits the highest minimum drag coefficient.

Although low drag is an important criterion, structural robustness must also be considered, in order to meet the design specifications of long-term reliability and resistance to mishandling. The final digit of a NACA designation gives the maximum foil thickness as a percentage of chord. 6% chord thickness was considered structurally fragile for the envisaged application and therefore the 0006 and 66-006 foils appear unlikely candidates. However they were retained for subsequent stages of the design process and analysis.

3.2 *Control Surface Configuration*

The vehicle's fins should incorporate both fixed stabilisers and moveable control surfaces. The two configurations shown in Figure 6 were considered: an all-moving tip outboard of the fixed stabiliser and a trailing edge flap.

Figure 6. Candidate Fin Configurations

Using similar areas for the moveable control surfaces, the lift: drag ratio for zero incidence on the stabiliser is plotted as a function of tip angle for the moving tip configuration in Figure 7 and as a function of flap angle for the trailing edge flap configuration in Figure 8. The results for all four candidate foil sections are presented.

Figure 7. Lift : Drag Ratio as a Function of Tip Angle for Moving Tip Configuration

Figure 8. Lift : Drag Ratio as a Function of Flap Angle for Trailing Edge Flap Configuration

In each case, the trailing edge flap gives a more favourable maximum lift: drag ratio, which is sustained over a broader range of flap angles. This is the configuration which was selected for the final design.

The geometry of the trailing edge flap was specified after consideration of the data presented in Figure 9 [7]. The effectiveness ratio of a wing flap is defined as the lift differential per degree angle of attack of the flap, in comparison to that of the surface as a whole, i.e.

$$\frac{dC_l}{d\delta} \Big/ \frac{dC_l}{d\alpha} = \frac{d\alpha}{d\delta}$$

where α = wing angle of attack, δ = flap deflection and C_l = lift coefficient.

Figure 9. Effectiveness Ratio versus Flap : Chord Ratio for Different Trailing Edge Flap Configurations

Figure 9 shows the relationship between effectiveness ratio and flap chord: wing chord ratio (c_f /c) for three geometric configurations: (a) full-span trailing edge flaps, (b) half-span trailing edge flaps, centrally located on the wing span, (c) half-span trailing edge flaps located at the outboard sector of the wing span.

According to Figure 9 full-span flaps are the most effective, but in the DOLPHIN layout, this would disturb the propeller approach flow [see Figure 1]. Therefore partial-span flaps were selected, to be located outboard of the propeller inflow region.

Figure 10. General Arrangement and Dimensions of the Control Surfaces on DOLPHIN

3.3 *Final Design of the Control Surfaces*

A parametric study of the effect of tail area and tail fin location on the stability of the DOLPHIN vehicle during steady cruise, using the experimental data published in Reference 4, was used to determine the final size and position of the tail fins. The fins were designed with a swept leading edge, to reduce the likelihood of entanglement in weed or debris.

The tail force required to turn a vertical circle of radius 100m was calculated to be 200N, or 100N per fin. The dimensions of the trailing edge flap, as presented in Figure 10, were calculated from this value; the flap:wing span ratio is 0.7 and the average flap:wing chord ratio is 0.38. The general arrangement and location of the fins on the prototype vehicle are also presented in Figure 10.

The final choice of wing section was limited to the laminar flow foils (66-006 and 66-009), because of their superior drag characteristics (Figure 4). Absolute values of the drag of the control surfaces, operating at 22 m/s in air (which gives a Reynolds No equivalent to the full size vehicle operating at 2.5 m/s in seawater) is presented in Figure 11 for these foils.

Figure 11. Drag Comparison for the Candidate Laminar Flow Aerofoil Sections [Full scale, 22 $m.s^{-1}$ in air]

Although the drag of the thicker, 66-009 section is marginally higher, the drag increment amounts to less than 1% of the total vehicle drag under steady cruise conditions. It was agreed that the mechanical advantages offered by a thicker section, such as robustness and ease of fabrication, more than offset the slight drag penalty and therefore the 66-009 section was selected for the final control surface design.

4. ACTUATOR DESIGN

4.1 *Design Considerations*

The design process for the control surface actuators focused on compactness and energy-efficiency. The limited power and space availability in a long distance AUV drives the requirement to minimise both the energy losses in the servo-mechanism and the space occupied within the hull. The main decisions therefore concerned the location of the servo-motor and the linkage between the motor and the shaft of the control flap.

The initial concept of locating the servo-motor inside the DOLPHIN hull was compared with the idea of fitting a pod on the wing tip, to house both the motor and the CTD sensor.

Figure 12. Comparison of Actuator Locations in the Hull (Internal) and Pod Mounted (External)

The two arrangements are presented schematically in Figure 12, with the relative advantages for each system. The elegant solution of a combined location for instrumentation and the servo-motor in the tip pod, which permits a simple linkage mechanism and ease of access for maintenance, while releasing valuable space within the vehicle hull, was finally selected. Reference 8 indicates that the additional drag will be small ($c_d \sim 0.05$, based on pod diameter) and that there may be a beneficial effect on the lift generated by the wing section, similar to end plates.

A design trade-off was conducted between the use of a pushrod or rotating shaft mechanism for the actuator linkage. Although the pushrod system is simpler and more efficient, this is offset by the disadvantages of a variable torque-arm and the possibility of buckling. Therefore a purely rotational system was the mechanism of choice.

Since the servo-motor shaft will be aligned with the axis of the tip pod (i.e. at right angles to the shaft of the control flap) a bevel gearbox or worm gear mechanism must be incorporated in the linkage. A bevel gearbox is smaller and more efficient, offering minimal backlash (which is advantageous for the controller design). The main benefit of using a worm gear is the unidirectional transmission, which can lock the fins in a given position, thereby reducing the energy required by the controller. However, the consequences of failure of the control system with fins locked could be catastrophic and the worm gear option was discarded.

4.2 *Final Actuator Design*

The final layout of the servo-motor and linkage is presented in Figure 13. A 12 volt D.C. motor is located in a pod at the tip of the control surface, behind the CTD sensor housing. The motor drive is transmitted via a 800:1 reduction planetary gearbox, through 1:1 nylon bevel gears which are connected to the control surface shaft. Nylon gears are particularly suitable in applications such as this, where zero backlash is required. The motor is housed in a pressure-balanced, oil-filled vessel, to accommodate operation at 6000 m depth in the ocean.

Figure 13 also illustrates the plate which provides access to a recess at the end of the control surface shaft, where the potentiometer which provides feedback on flap deflection for the vehicle controller will be located. Controller design will be the subject of a future publication.

5. MODEL TESTING

5.1 *Experimental Procedure*

Testing of a full-scale model of a single control-surface and actuator was performed in a low speed wind tunnel at the University of Southampton. The tunnel has a working section of 7' ∞ 5' and a maximum air speed of 44 m/s. The tests were conducted at 22 m/s, providing a Reynolds No corresponding to full-scale vehicle operation at 2.5 m/s in seawater and also to the half-scale model wind tunnel tests described in Reference 4.

The fin was vertically mounted above a false floor, extending 2.5 m in front and 0.6 m to the rear, which ensured nal Design of the Control Surface Actuator

the same boundary layer thickness as that at the tail fin location on the DOLPHIN hull, under normal operating conditions. The fin was supported by a 5-component dynamometer beneath the false floor, giving measurements of axial and side force, and bending moments about three orthogonal axes. An automated data acquisition system logs the average and standard deviation of 4 sample voltages from each of the dynamometer strain gauges for a given test condition.

Trials were conducted for fin angles of attack between -16° and +16° to the tunnel axis, in steps of 2°. For each fin angle, the angle of the trailing edge flap was varied between –14° to +14° to the fin, again in steps of 2°.

Smoke injection and fibre tufts (attached to the fin and flap) were used to visualise the flow.

5.2 *Experimental Results*

Preliminary analysis indicates a fair correlation between the theoretical lift data used in the design calculations and the measured values from the model tests (see Figure 14).

Figure 14. Comparison of Lift Forces from Wind Tunnel Tests with Theoretical Calculations

Although the empirical lift values are lower than theory, the specified lift force of 100N is generated during tests with a flap deflection of 7° and the foil has not stalled at 14° deflection, when the lift force exceeds 200 N.

Comparison of the experimental drag data with theory is less satisfactory, as shown in Figure 15. The two empirical data points at 0° and 12° flap deflection which indicate negative drag must be disregarded and the remaining values are between 25% (for large angles of deflection) and 75% (for small angles of deflection) lower than indicated by the theoretical design calculations. The discrepancy may have been caused by experimental error; there is a suspicion that the dynamometer or model was fouling on the false floor of the tunnel. This is the probable explanation for the two 'rogue' data points in Figure 15.

Figure 15. Comparison of Drag Forces from Wind Tunnel Tests with Theoretical Calculations

Full analysis of the test results, which is on-going at the time of writing, will be the subject of a future publication.

6. CONCLUSION

The design of the control surfaces and actuators for the Autosub DOLPHIN vehicle have been presented. Wind tunnel tests confirm that the tail lift force required to achieve the specified vehicle manoeuvrability is generated with a flap deflection of 7°, which is well below the flap stall angle. The corresponding drag measurements were lower than expected and this area requires further analysis.

7. ACKNOWLEDGEMENTS

The authors wish to thank Dr R Allen, Dept of Mechanical Engineering and Miss H Jones, Department of Electronics and Computer Science, University of Southampton, for their contributions to this project. The work was carried out as a Master of Engineering Group Design Project in the Faculty of Engineering, University of Southampton and generously sponsored by the Ocean Technology Division of the Southampton Oceanography Centre.

8. REFERENCES

[1] B. S. McCartney and P. G. Collar, "Autonomous Submersibles – Instrument Platforms of the Future," *Underwater Technology*, **15**(4), pp.19-25, 1989.

[2] B. H. Carmichael, "Underwater Vehicle Drag Reduction through Choice of Shape," *AIAA Second Propulsion Joint Specialist Conference,* Colorado Springs, Colorado, Paper No. 66-657, 1966.

[3] J. S. Parsons, R. E. Goodson and F. R. Goldschmied, "Shaping of Axisymmetric Bodies for Minimum Drag in Incompressible Flow," *Journal of Hydronautics*, **8**(3), pp.100-107, July 1974.

[4] A. Huggins and A. R. Packwood, "Wind Tunnel Experiments on Fully Appended Laminar Flow Submersible for Oceanographic Survey," *Ocean Engineering*, **22**, pp. 207-221, Feb 1995.

[5] R. J. Babb, "Instrumentation for a Low Drag Hydrodynamic Test Vehicle," *IEE International Conference on Electronics in Oceanography*, Cambridge, UK, pp. 24-30, July 1994.

[6] F. W. Riegels, "Aerofoil Sections – Results from Wind Tunnel Investigations," Theoretical Foundations, 1961.

[7] S. F. Hoerner, "Fluid-Dynamic Lift" Publ. L. A. Hoerner 1975.

[8] S. F.Hoerner, "Fluid-Dynamic Drag" Publ. S. F. Hoerner 1965.

SYMBOLS

α	angle of attack for wing
δ	flap deflection angle
C_l	lift coefficient $C_l = \dfrac{L}{1/2\,\rho\, v^2\, A}$
Re	Reynolds No. $\mathrm{Re} = \dfrac{v\, l}{\nu}$
C_d	drag coefficient $C_d = \dfrac{D}{1/2\,\rho\, v^2\, A}$
L	lift force (N)
D	drag force (N)
v	velocity (m.s^{-1})
l	length (m)
A	area (m^2)
ρ	density (kg m^{-3})