VALIDATION OF THE HYDRODYNAMIC & MANEUVERING MODELS FOR THREE LEGACY UNDERSEA GLIDERS

Douglas E. Humphreys
Vehicle Control Technologies, Inc.
dhumphreys@vctinc.com

Jim Osse
University of Washington
jimo@ocean.washington.edu

Clayton Jones
Webb Research Corporation
cjones@webbresearch.com

Abstract

The US Navy is currently studying the performance characteristics for a variety of glider platforms and system concepts beyond those currently used for oceanographic data gathering.

In preparation of potential new glider developments, ONR requested that VCT develop high fidelity hydrodynamic, dynamic and control models for each of the current legacy gliders; the University of Washington APL Seaglider, the Webb Research Corporation Slocum glider, and the Scripps Institution of Oceanography Spray glider.

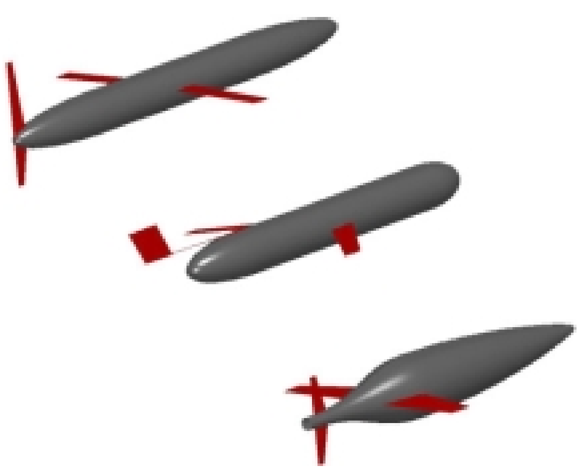

Figure 1 · Three Legacy Undersea Gliders

Utilizing the VCT database of more than 240 vehicles and its modeling and simulation program (VCT Tools™), hydrodynamic models for each of the gliders were developed using inputs of geometry and mass characteristics. The vehicle model is a full 6-DoF non linear rigid-body model that consists of individual geometry components reacting to flow conditions in each geometry component's local angle of attack/sideslip.

Static performance measures consisting of classical C_L , C_D , C_L/C_D and $C_L^{2/3}/C_D$ plots as a function of angle-of-attack and glide angle are presented here, along with glide polar performance plots. VCT predicted static performance is compared to in-water data, showing a very good match.

VCT Tools™ was then used to develop and integrate the hydrodynamic models, actuator, motor propulsion, and buoyancy control models that were required for validating the model against in-water maneuvering data. Equations of motion and numerical methods for solving the equations in both the time domain and frequency domain are legacy codes that have been in use by VCT personnel to model and simulate over 200 undersea vehicles for the past 20 years.

Results from this study validated the VCT design and analysis tools for use in glider

development and showed that high fidelity hydrodynamic models do not in all cases require tow tank or wind tunnel test data.

Undersea Glider Performance Metrics

US undersea gliders that are currently in production fly at small angles of attack, small lift-to-drag ratios (L/D) and large flight path angles (γ). Because of the sharp-edged gradient structures of ocean properties, emphasis for these designs was on optimizing the performance of the gliders to travel up and down through the water column at rather steep glide angles; as opposed to optimizing them for cross country performance as in conventional sailplanes.

Key gliding performance measures of effectiveness for undersea gliders are the same as those for sailplanes; flight path angle (γ) (glide angle is –γ), angle of attack (α), pitch angle (θ), dive/climb velocity and horizontal velocity. These parameters are related by the following equations:

$$\text{Flight Path Angle} = \text{Pitch Angle} - \text{Angle of Attack}$$

$$\gamma = \theta - \alpha$$

$$\text{Tan}\ \gamma = \frac{-1}{C_L/C_D} = \frac{-1}{U/W}$$

The lift-to-drag ratio and the net buoyancy (propelling force) are major factors in determining glider performance.

Lift is relatively linear to angle of attack, with only a small amount of nonlinearity at angles of attack above 10°. However, drag is quite nonlinear to angle of attack, Reynolds Number (Re No.) and surface roughness. Furthermore, the change in C_D does not vary monotonically with Re No. (Figure 2).

Drag has classically been divided into several categories for discussion purposes:

> Skin friction drag > Form drag
> Induced drag > Base drag

Of these categories, skin friction drag of the hull represents about 50% of the drag for a glider with zero surface roughness and no protuberances. The hull-alone, smooth surface drag coefficients are remarkably similar for the three hull shapes used for these legacy gliders. However, variations in surface roughness, the design and integration of external sensors (e.g., CTD, acoustic pinger, communication antenna), and other hull cut-outs or protuberances cause the drag to differ by 50% or more among the three legacy gliders.

It is well known that the skin friction drag coefficient varies with Re No. and surface roughness condition. Roughness is commonly expressed as an equivalent sand grain diameter (k or SGD) after Schlichting[1] and Hoerner[2].

$$k = 1\ \text{mill} = 0.001\ \text{in} = 1\ \text{SGD}$$

Schlichting offers a C_D vs Re No. relationship that is non-dimensionalized by the ratio of sand grain diameter (k) and characteristic length (L), or k/L.

Using tables from the literature (F-16 aircraft[3], Hoerner[2]), one can convert surface finish condition to an equivalent sand grain diameter. Typical surface finishes found on undersea vehicles are as follows:

Surface	SGD
Polished Surface	0.02
Sheet Metal (Aircraft Type)	0.1
Smooth Spray Paint	0.2
Planed Wood	0.6
Production Spray Paint	1
Steel Plating – Bare	2
Dipped Galvanized Metal	6
Sand Cast Surface	10

[1] Schlichting, Hermann, Boundary Layer Theory, McGraw-Hill, New York, 1951.

[2] Hoerner, Sighard F., Fluid Dynamic Drag, June 1965

[3] F-16 Training Manual : How to Read and Use Engineering Drawings, USAF TR X-YY, 1976.

The equivalent SGD is then non-dimensionalized by the characteristic length (hull length for hulls, chord length for fins and wings). Using Schlichting's[1] non-dimensional k/L curves, one can then compute skin friction drag coefficient as a function of surface roughness and Re No.

Figure 2 presents the VCT computed drag coefficient for the hull-alone (not the fully appended vehicle) at 0° angle of attack. Plotted on the y-axis is total C_D, which includes skin friction drag, profile drag and induced drag (may be non-zero at 0° angle of attack if vehicle is asymmetrical; e.g., wing with incidence). The reference area for C_D in Figure 2 is $Vol^{2/3}$. In order to simplify the conversion between various non-dimensionalizations for C_D and Re No., Figure 3 presents C_D as a function of SGD and speed, where C_D is non-dimensionalized by $Vol^{2/3}$. These same C_D vs Re No. plots for the fully appended vehicle at 0° angle of attack are presented in Figure 4.

A key point to be made from these drag plots is that for this size vehicle and the speed range from 0.1 to 1.0 KTS, drag varies by a factor of 3 depending on speed and the amount of surface roughness. At speeds above 10 KTS, drag variation is only 40%.

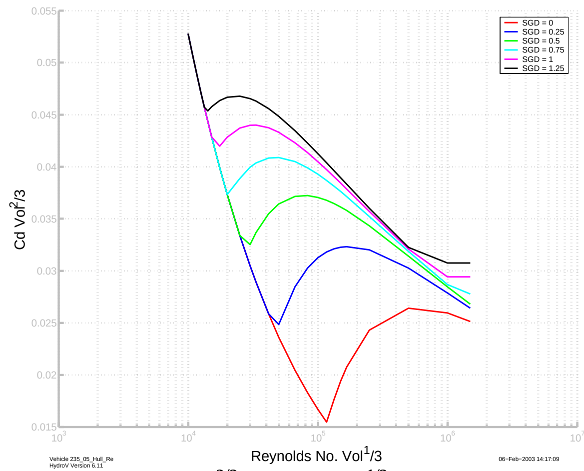

Figure 2 · C_D ($Vol^{2/3}$) vs Re ($Vol^{1/3}$) for Various Surface Roughness Conditions, Hull Alone

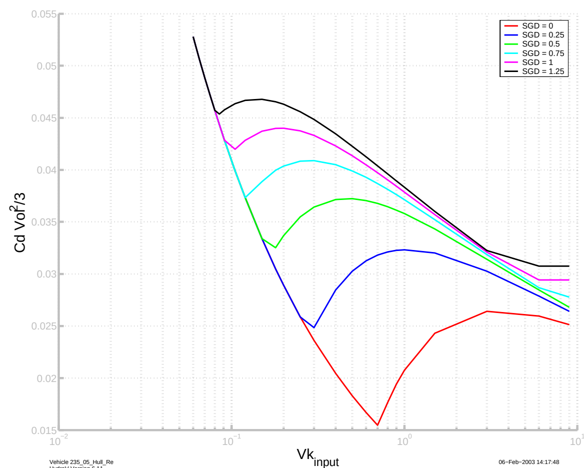

Figure 3 · C_D ($Vol^{2/3}$) vs Speed (KTS) for Various Surface Roughness Conditions, Hull Alone

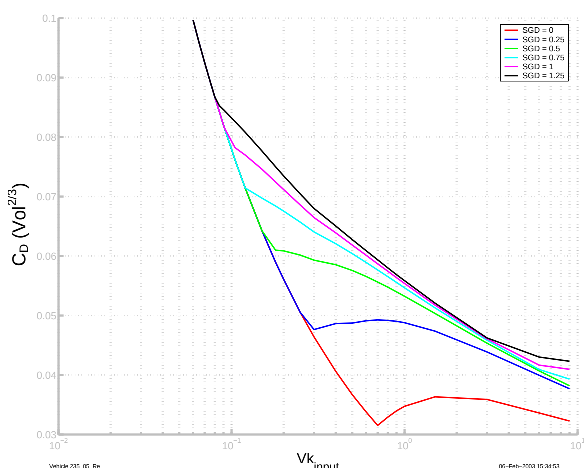

Figure 4 · C_D ($Vol^{2/3}$) vs Speed (KTS) for Various Surface Roughness Conditions, Fully Appended Vehicle

The key gliding performance metrics [flight path angle (γ) (glide angle is –γ), angle of attack (α), pitch angle (θ), dive/climb velocity and horizontal velocity] can be combined into a single plot that gives increased insight into how these parameters relate to each other. This is called the glide polar (Figure 5) (taken after Osse[4]).

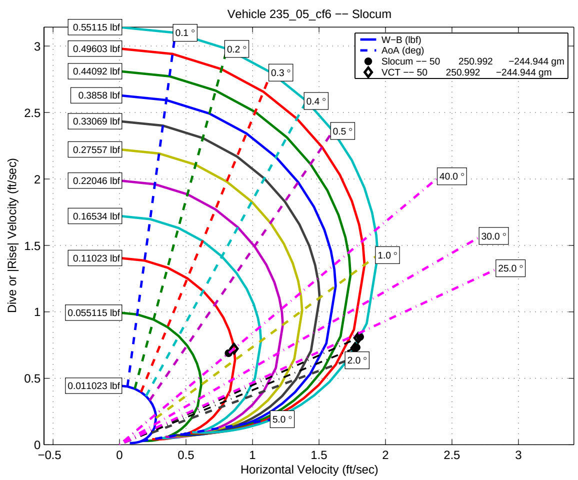

Figure 5 · Glide Polar for Slocum Glider

In this glide polar plot, horizontal velocity is plotted on the x-axis (u-component of total speed, U_0), and vertical velocity is plotted on the y-axis (w-component of total speed). The solid circular-arc lines are lines of constant net buoyancy, defined as air weight minus displaced weight, or W-B. Dashed lines of constant angle of attack and/or X_{CG} location are overlaid on the plot to show the relationship between glider configuration and performance. Lines for constant glide angle values of 25°, 30° and 40° are plotted for reference.

Another presentation of the performance parameters is presented in Figure 6, where angle of attack is plotted against X_{CG} position, trim pitch angle and glide path angle.

[4] Ericksen, C.C., Osse, T.J., et. al., "Seaglider: A Long-Range Autonomous Underwater Vehicle for Oceanographic Research", IEEE 2000.

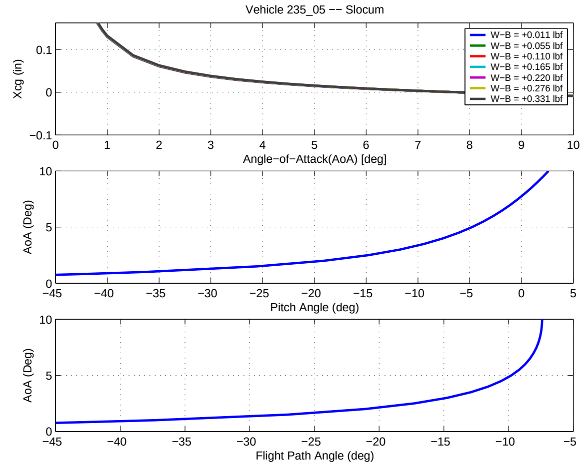

Figure 6 · Glider Angle of Attack, Pitch Angle and Flight Path Angles

Model Validation Using Vehicle Trim Data

Figure 7 presents the important non-dimensional aerodynamic parameters for gliding flight, C_L/C_D and $C_L^{2/3}/C_D$. These parameters are plotted against angle of attack in the top plot and C_L in the bottom plot. The point at which C_L/C_D is a maximum is the shallowest glide angle, since

$$\tan\gamma = \frac{-1}{C_L/C_D}$$

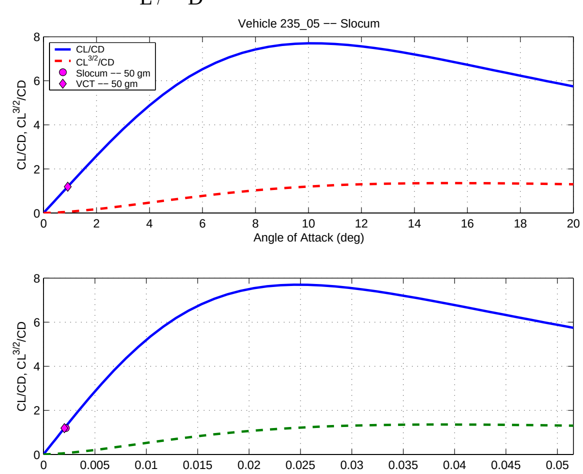

Figure 7 · Hydrodynamic Model Validation against Static Trim Data

For the Slocum vehicle, C_L/C_D max = 7.9, resulting in a minimum glide angle of 7.2°, which is at angle of attack=10° or C_L=0.025. (The reference area for C_L and C_D is the hull length squared, where L = 5.866 ft.)

The validation operating conditions for Slocum are indicated by the symbols (data) and (VCT simulation), which are nearly on top of each other. Test conditions for validation are annotated in Figure 5.

Two data sets were used in the validation of the static trim conditions. The first set is for an earlier configuration with higher drag than the present design and was tested with a net buoyancy of 50g. The second set is from recent in-water testing, where the net buoyancy was set to 250g. Both rise and dive data are included in this second set. In the first data set, the VCT model predicts a higher speed than that reported in the literature. The speed match for the second set is excellent. The same hydrodynamic model was used in both comparisons.

Model Validation Using Vehicle Maneuvering Data

Maneuvering data has been provided by each of the glider builders. For two of the gliders, the VCT simulation is in excellent agreement with the data. For the third glider, issues with laminar flow vs turbulent flow regions on the hull could account for the differences between simulation and data. The simulation was run for both fully turbulent flow (green curve) and fully laminar flow (blue curve).

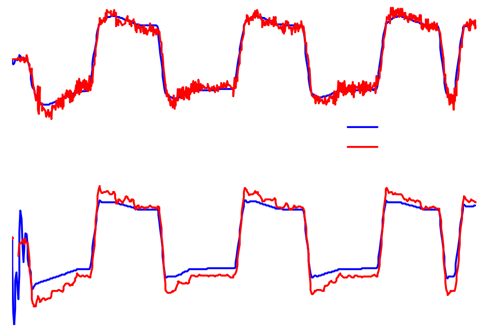

Figure 8 · Model Validation against Maneuvering Data – Slocum Glider

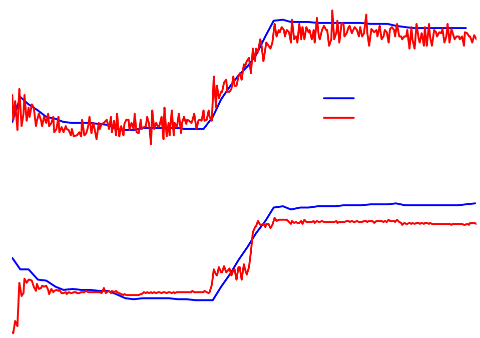

Figure 9 · Model Validation against Maneuvering Data – Spray Glider

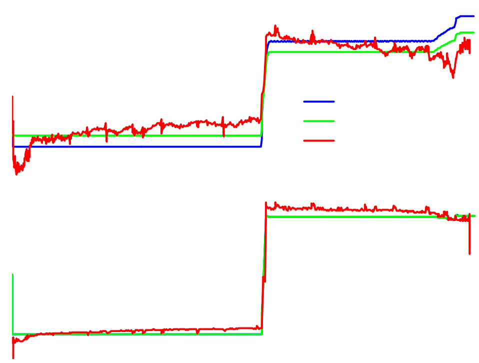

Figure 10 · Model Validation against Maneuvering Data – Seaglider

Summary & Conclusions

The hydrodynamic characteristics of the Slocum glider have been modeled using VCT Tools™. An excellent match for both the static performance and maneuvering data was obtained between the experimental data and the VCT simulation.

Although it is customary to use tow tank force and moment data to validate simulation models and to guide the adjustment of key hydrodynamic parameters, the excellent match between the data and the VCT simulation was achieved without tow tank or wind tunnel data for any of the glider configurations. This achievement was made possible by the continuous improvement to VCT flow phenomena models throughout the past 30 years and the preponderance of previous validation efforts using tow tank, wind tunnel, rotating arm and full-scale in-water data for a variety of vehicles ranging from submarines, torpedoes, UUVs, air vehicles, to towed vehicles. The validation of the VCT physics-based model provides a high degree of confidence for the use of these same model development methods to support any vehicle control system development.