IMPACT OF THE HYDRODYNAMIC NONLINEAR MANEUVERING MODEL FIDELITY ON COMPARISONS WITH IN-WATER DATA

Douglas E. Humphreys
Kenneth W. Watkinson

Vehicle Control Technologies. Inc.
11180 Sunrise Valley Drive · Suite 350
Reston, VA 20191 · www.vctinc.com

703·620·0703 · info@vctinc.com

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Abstract

This paper describes the impact of the hydrodynamic nonlinear maneuvering model fidelity on UUV maneuvers.

A VCT model that had previously been developed without the benefit of modern CFD methods is compared to data. The hydrodynamic model is then updated using recent developments in CFD and again compared to the same data.

Advancements in hydrodynamic technology over the last few years have taken hydrodynamics to a new level of modeling accuracy that rivals the accuracy of experimentally based approaches at a much lower cost. In the new methodologies, contributions to the body and fin surfaces are computed using a combination of techniques, which are both CFD-based and semi-analytical. The CFD code developed by VCT tracks the hull vorticity and computes the point where the hull wake is shed, based on a method similar to that used to compute the Kutta condition for a wing. The semi-analytical methods have a theoretical/analytical basis, but also include factors that are evaluated from a broad parametric experimental database. Interference effects, such as fin-to-fin and fin-to-body, are now computed using the vorticity based CFD models. In addition to improving the static terms to the equations of motion ($Z'w$, $M'w$, $Y'v$, $N'v$, etc.), the CFD code improves the computation of the added mass terms and the computation of damping effects ($M'q$, $Z'q$, $N'r$, $Y'r$) due to the vehicle hull. Consistent damping terms are difficult to measure experimentally due to inaccuracies in rotating-arm and PMM facilities. VCT's new methods have shown consistent improvement throughout a wide variety of vehicle applications ranging from a 6" diameter high-speed weapon to a 400 FT long submarine.

Background

The example considered in this paper is the integrated hydrodynamic and control system design for an Unmanned Underwater Autonomous Vehicle (UUAV). The hydrodynamic design included the evaluation, redesign and testing of a new fin/afterbody configuration.

The UUAV considered in this paper must operate over a range of buoyancy conditions and CG-CB offset configurations at speeds around 5 KTS. This range of buoyancy and trim conditions results from variation in environmental conditions and variations from one vehicle to another. Operation at low speeds within this range of buoyancy and trim conditions establishes challenging control requirements for the vehicle, a design problem common to many UUVs.

The initial control surface design provided insufficient control authority over this wide range of operating conditions. The design constraint to keep the control surfaces within the body diameter poses a challenging requirement for static control surface lift production. The dynamic lift needed for adequate autopilot control system performance places additional requirements on the control surface design.

Maintaining control during surface launch presents the most demanding dynamic lift requirement. The UUAV must maintain control during water entry at a relatively high speed from a helicopter launch and at a very low speed from a surface craft launch. The large variation in vehicle control characteristics over launch conditions and the submerged operating envelope presents a significant challenge to achieving adequate control system performance, both on the control algorithm itself and the hydrodynamic design. The design approach required accurate linear and nonlinear vehicle models and carefully designed margins in the autopilot feedback control system. This integrated hydrodynamic and control system design process was performed using models developed with VCT's HydroV™ and SimV™ programs. These programs were used in a model-based, simulation-based design methodology developed at VCT.

Figure 1 illustrates one of the key design attributes for the vehicle. At low speed, there must be sufficient control authority over a wide range of operating buoyancy and trim conditions. The boxed operating area in the figure shows the boundaries for X_{CG} and weight that meet vehicle requirements – specifically, showing the needed control authority (no more than 20° of elevator required for steady-running). If adequate control surface authority could not have been achieved in order to fly the vehicle throughout this range, an additional CG shift device would have been required to achieve good control characteristics. The larger boxed area represents the operating range with the CG shift device. One objective of the design was to make the smaller box large enough to provide an operationally effective vehicle, thereby avoiding the addition of a CG shift device. The design attributes quantified in Figure 1 are examples of the key performance metrics that were tracked throughout the integrated hydrodynamic and control design process.

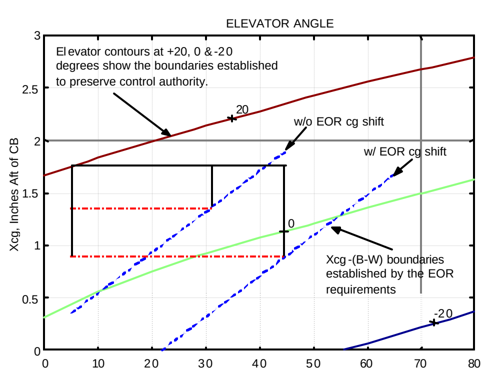

Figure 1 · Buoyancy and trim operating envelope, elevator angle contours

Static Trim

One of the attributes of this UUAV is its low cost. Trade studies were conducted to determine the cost benefit of including a vehicle trim system versus developing a high fidelity hydrodynamic model that could be used to accurately set the weight and X_{CG} limits of the vehicle. The development of the high fidelity modeling approach won out over the trim system largely due to its non-recurring cost advantage. This process involved the development of a physics based, geometry driven model, body build-up type wind tunnel tests, and detailed correlation of the physics based model to the wind tunnel data to ensure an accurate and consistent model.

One of the metrics used during the design cycle to ensure adequate control authority was the stern plane angle required for static trim. Not only is this an important requirement for the vehicle system, it has also been found to be a good indicator of dynamic fin authority required for maneuvers. Three hydrodynamic models were used during the development cycle. The first model was developed during the proposal stage and was adequate for concept trade offs but not for detail design. The second model was the semi-empirical model developed during the preliminary and detail design phases and validated with wind tunnel and limited ADM testing. The third model, which is the highest fidelity of the three, was developed during EDM when it came time to validate the full range of weight-X_{CG} operations. This third model incorporated new CFD methods to compute hull static and dynamic forces and moments.

Figure 2 shows the vehicle weight and X_{CG} operating bounds based on the conceptual design model. This model indicated that the design achieved the required weight range from 2808 LBS (zero net buoyancy) to 2728 LBS (80 LBS light). The X_{CG} range of operation was from +0.05 FT ahead of the center of buoyancy to -0.025 FT behind the center of buoyancy. The allowable X_{CG} travel was about half of what was ultimately required.

Using the data from the wind tunnel tests of the final configuration, the range of allowable travel was improved dramatically, increasing to 0.13 FT of travel at the low weight and 0.16 FT at the high weight (Figure 3).

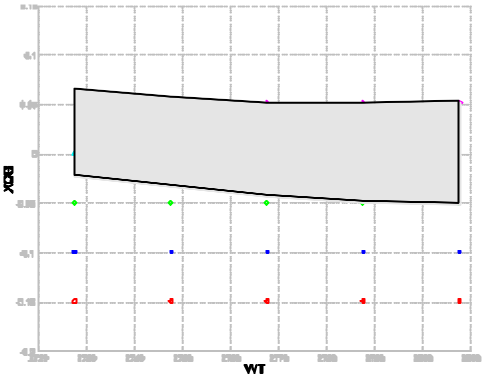

Figure 2 · Weight-X_{CG} Operating Boundaries based on Conceptual Design Model

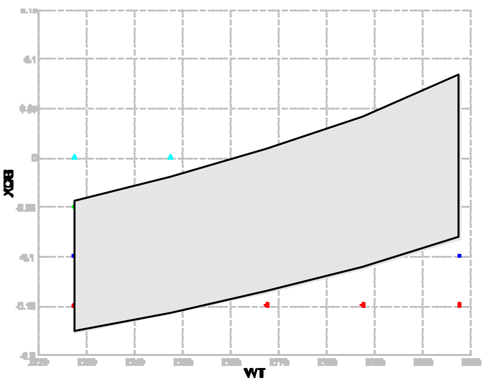

Figure 3 · Weight-X_{CG} Operating Bounds base on Preliminary Design Model

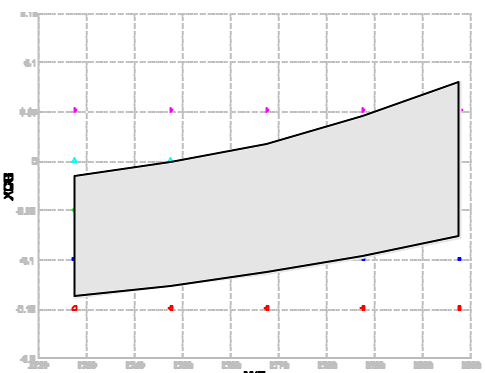

Figure 4 · Weight-X_{CG} Operating Bounds based on CFD-Based Model

An important point to note here is that there is a region of weight-X_{CG} coverage that is not overlapping between the two models. At the low weight, the conceptual design model allowed the CG to travel as far forward as +0.075 FT **ahead** of the center of buoyancy while the preliminary design model shows that the farthest forward the CG can travel is 0.05 FT **behind** the center of buoyancy. The impact on the design was that components had to be shifted around to make up for 330 FT-LBS of moment. Even more important is that if the model had not been refined, then the vehicle would not have been controllable in the non-overlap regions. The model developed using the CFD-based techniques resulted in small but significant shifts in the weight-X_{CG} allowable region (Figure 4).

One might wonder how the difference between the second and third models compares to the wind tunnel data. Figure 5 presents the preliminary design model compared to the pitch moment data from the wind tunnel test. This agreement with data is excellent over the linear angle of attack (AoA) range and good over the nonlinear range. One would expect this level of agreement to be more than adequate for engineering design purposes. Now compare the CFD-based model with the wind tunnel data (Figure 6). It is seen to be excellent over the linear range and very good over the non-linear range. These subtle differences created a difference of 2.5° in the trim AoA condition and significant shift in the allowable X_{CG} range of travel. The non-linearity exhibited in the pitch moment curves is even more pronounced in the lift curve (Figure 7).

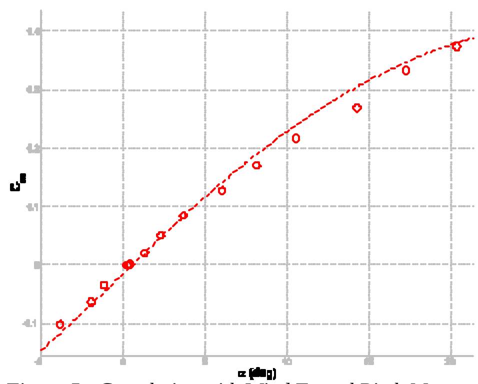

Figure 5 · Correlation with Wind Tunnel Pitch Moment Data, Preliminary Design Model

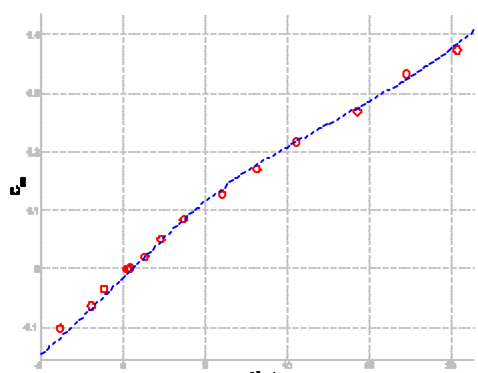

Figure 6 · Correlation with Wind Tunnel Pitch Moment Data, CFD-Based Model

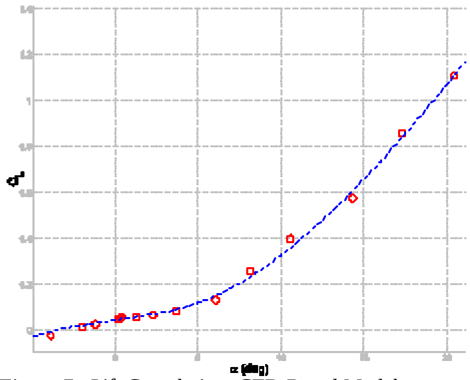

Figure 7 · Lift Correlation, CFD-Based Model

Maneuver Time Histories

Simulations were run for a surface launch and swim out to constant speed, heading and depth. Three weight-X_{CG} configurations were selected; one from each of the boundaries determined by the following:

- the CFD-based model
  X_{CG} = *-0.05 FT and weight = 2747 LBS* (UUAV-1)
- the preliminary design model
  X_{CG} = *-0.16 FT and weight = 2747 LBS* (UUAV-2)
- the concept design model
  X_{CG} = *+0.04 FT and weight = 2727 LBS* (UUAV-3)

The simulated trajectories are plotted in Figure 8, Figure 9 and Figure 10 for each of the weight-X_{CG} conditions. The weight-X_{CG} conditions predicted to be valid for using the conceptual and preliminary design models are not able to achieve the commanded pitch, depth or heading. The control surface activity for the CFD-based condition is small while the concept design condition is in a limit cycle using maximum fin deflection and the preliminary design condition experiences large excursions while still not controlling the vehicle.

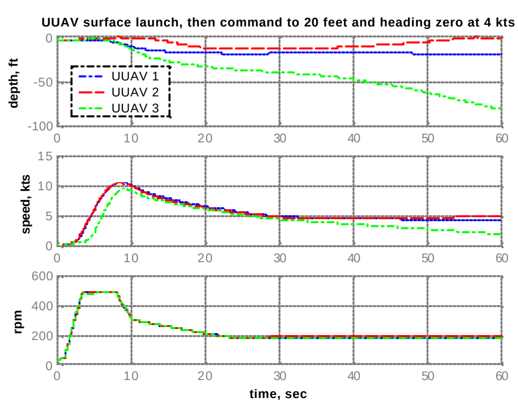

Figure 8 · Depth, Speed, RPM Simulations from the three models

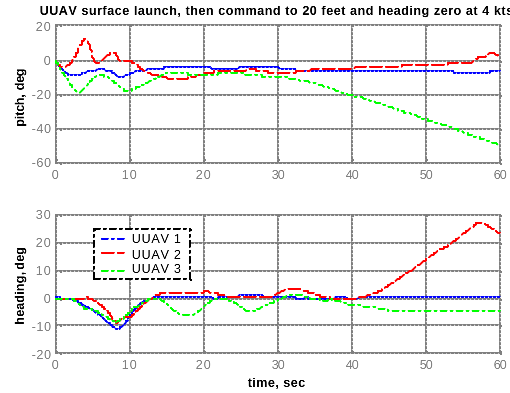

Figure 9 · Pitch and Heading Simulations from the three models

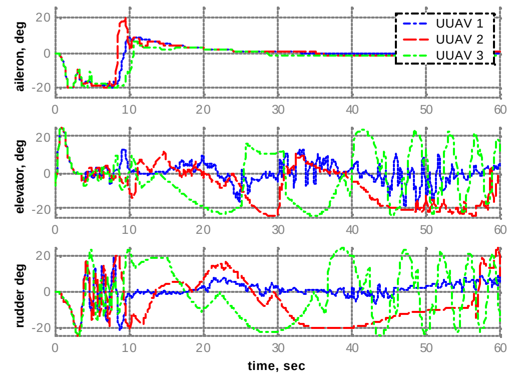

Figure 10 · Control Surface Activity

Comparisons with In-Water Data

This same improvement in model fidelity has been observed in several other vehicles developed by VCT. Figure 11 and Figure 12 presents the comparisons between the simulation and in-water data for a high-speed torpedo.

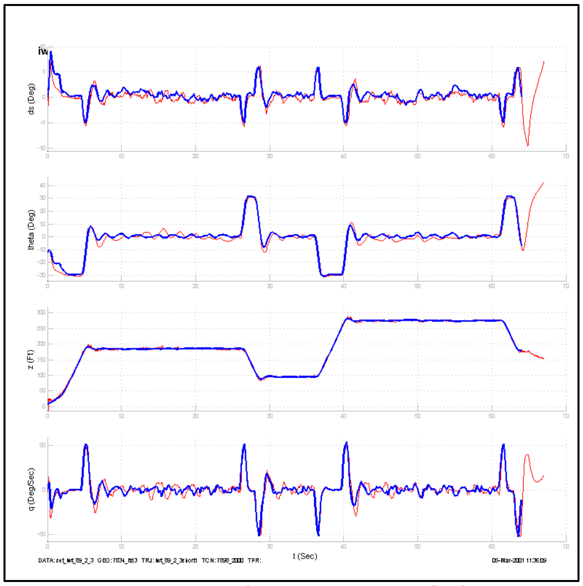

Figure 11 · Comparison with In-Water Data, Pitch Plane

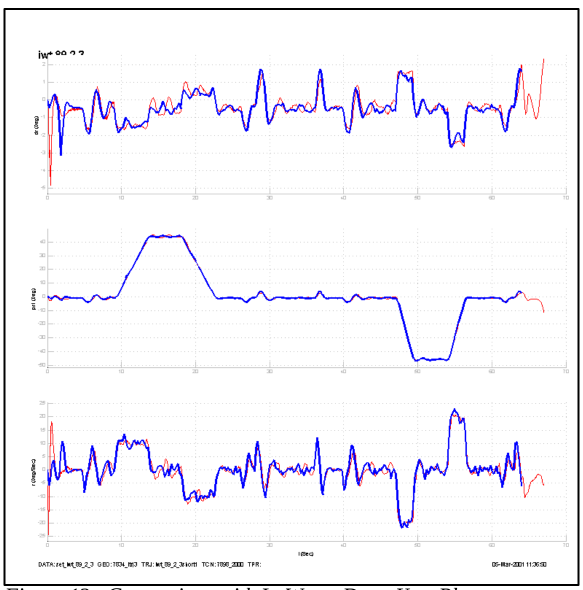

Figure 12 · Comparison with In-Water Data, Yaw Plane

The in-water comparisons include a rapid depth change with high pitch rate, both dive and climb, and a heading doublet

Pitch and pitch rate control behavior during the depth change shows excellent agreement between the new model and data. While the pitch angle achieved is determined by the characteristics of the control system, the control surface deflections required to follow the commanded pitch time history is determined by the vehicle hydrodynamic characteristics. In order for the simulation model stern plane deflection time history to match this well, the model must capture many different aspects of the vehicle hydrodynamics; among these are the damping, control surface authority, and body lift and moment due to angle of attack.

An important attribute of the new model is apparent in the depth change maneuver. The out-of-plane behavior of the heading-keeping autopilot during this depth change is very well modeled. The rudder and yaw time histories during this depth change maneuver are very well matched. This means that the lateral hydrodynamic forces and moments due to longitudinal motions (out-of-plane motions) are also well modeled. These hydrodynamic phenomena are among the most difficult to extract from tow tank test data.

The heading doublet maneuver is a 45° heading change with a rate limit of 20 DEG/SEC. Examining the details of the control activity reveals that the hydrodynamic model captures both the in-plane and out-of-plane hydrodynamic characteristics, as with the depth change maneuver. The rudder deflection necessary to cause the turn and hold it at the desired turn rate is very well modeled. The stern plane response shows that the model is capturing the principal out-of-plane forces and moments induced by the heading changes.

The most challenging hydrodynamic modeling configuration is the submarine. This is due to the vortex shed from the sail during a turn causing large out of plane pitch motions.

A recent set of experiments using a free-running submarine-like model were performed to support the development and validation of CFD codes for maneuvering simulation.

A controlled turn using 35° rudder is shown below. The agreement between the in-plane state variables (sideslip, yaw rate, turn diameter) is excellent. The agreement in roll and roll rate is very good. For the out-of-plane variables (angle of attack, pitch, pitch rate, and depth) the agreement is good, with some phasing differences between the simulation and the data.

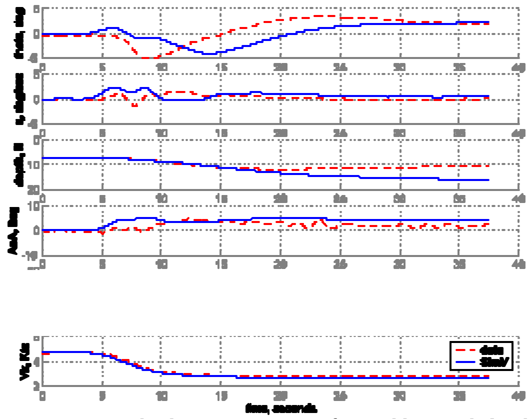

Figure 13 · Pitch Plane Comparisons for Highly Coupled Vehicle

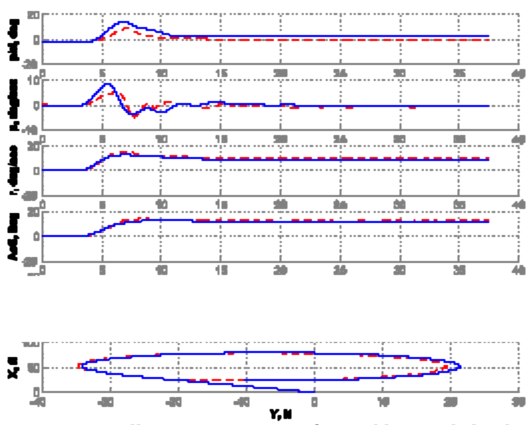

Figure 14 · Roll-Yaw Comparisons for Highly Coupled Vehicle

A critical component to the fidelity of the VCT maneuvering model is the tracking of the sail tip vortex and the loads induced on the hull and the aft fins throughout an unsteady maneuver. Plots of the vortex path and its strength are presented in Figure 15.

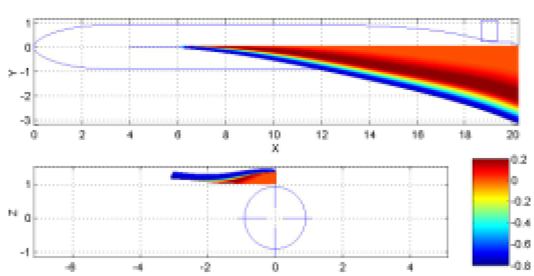

Figure 15 · Track of Sail Vortex during a Turn