Computational Hydrodynamics and Control Modeling for Autonomous Underwater Vehicles

David L. Bradley
The Pennsylvania State University
Applied Research Laboratory
P.O. Box 30, State College, PA 16804-0030
Phone: 814-863-9916 Fax: 814-863-8783 email: dlb25@psu.edu

Grant Number: N000149810904
http://www.arl.psu.edu

LONG-TERM GOALS

The long-term objective of the program is to develop predictive technologies to support virtual design and evaluation of underwater vehicles systems. CFD technologies will be used to predict hydrodynamic models for AUVs and those models will be coupled with control system design and modeling tools to allow vehicle conceptual designs to be evaluated within the context of a realistic mission. Use of these technologies will reduce the cost associated with experimental testing and the evaluation of a larger number of design options will result in vehicle systems with better overall performance. The next phase in the development of these capabilities is to extend the capabilities of the CFD technologies to enable modeling of AUVs in very shallow water. Models for the dynamic environment including bottoms and free-surface with waves have already been developed and need to be coupled with the vehicle models described in this report. Basic and applied research will be required to characterize the operation of AUVs in this environment for the purpose of performance assessment since existing reduced-order model formulations are not applicable.

OBJECTIVES

The objectives of this effort were to compare the forces and moments acting on a maneuvering AUV predicted by computational fluid dynamics (CFD) code with similar data collected aboard an operational AUV. In particular, the multi-block Navier-Stokes flow solver UNCLE (Unsteady Computation of Field Equations) was used in this effort. Methodologies and software tools were developed to utilize vehicle maneuvering data (simulated and real) to directly predict AUV hydrodynamic models. The results of the study were used to improve the performance of an existing AUV for which no constrained model test data exists.

APPROACH

Simulations of maneuvering AUVs were conducted using the UNCLE code and the resulting net force and moment data were used to estimate first-order stability derivatives. Results were produced for two AUV body shapes; one for which model test data is available and one for which only free-running operational data is available. The SUBOFF body shape without appendages was used as a reference shape to perform initial code verification. Stability derivatives derived from the CFD data compare well with published experimental results. The UNCLE code used to predict the forces on the SUBOFF

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**

4. TITLE AND SUBTITLE **Computational Hydrodynamics and Control Modeling for Autonomous Underwater Vehicles**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **The Pennsylvania State University,,Applied Research Laboratory,P.O. Box 30,,State College,,PA, 16804**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The long-term objective of the program is to develop predictive technologies to support virtual design and evaluation of underwater vehicles systems. CFD technologies will be used to predict hydrodynamic models for AUVs and those models will be coupled with control system design and modeling tools to allow vehicle conceptual designs to be evaluated within the context of a realistic mission. Use of these technologies will reduce the cost associated with experimental testing and the evaluation of a larger number of design options will result in vehicle systems with better overall performance. The next phase in the development of these capabilities is to extend the capabilities of the CFD technologies to enable modeling of AUVs in very shallow water. Models for the dynamic environment including bottoms and free-surface with waves have already been developed and need to be coupled with the vehicle models described in this report. Basic and applied research will be required to characterize the operation of AUVs in this environment for the purpose of performance assessment since existing reduced-order model formulations are not applicable.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

body was modified so that simulations could be conducted of the Seahorse AUV developed at the Applied Research Laboratory / Penn State University and operated by NAVOCEANO. Since experimental data does not exist for this body, data recorded during normal in-water operation was used to predict stability derivatives. The available data indicate that the results from the UNCLE code are sufficiently accurate for the design of control systems and prediction of vehicle operational performance.

One of the novel aspects of the approach being pursued at the Applied Research Laboratory is the use of unsteady data to develop simulation models for underwater vehicles. Unlike traditional approaches where CFD is typically used to simulate constrained model tests, the ARL approach utilizes dynamic data from multiple simulations to estimate a model. The advantage of this approach is that it is equally applicable to tow-tank or water tunnel data, CFD generated data, and in-water data.

WORK COMPLETED

The first configuration studied was the un-appended SUBOFF shape. The body is cylindrical in cross-section and has a blunted conical nose and tapered tail. A 131 x 51 x 33 C-type grid system was used to discretize the fluid domain on and around the body. In order to isolate the effects of the outer boundary, the far field boundary was placed at a distance of 15 body lengths upstream of the nose and outboard of the body. Turbulent viscous solutions were obtained for this body at angle-of-attacks ranging from zero to fifteen degrees. The Reynolds number based on the length of the hull was about 14 million. In addition to the steady angle of attack cases, a set of prescribed motion cases were run for the SUBOFF body undergoing a plunge motion. Prior to beginning the unsteady plunging motion, the numerical code was run until a steady state flow condition was modeled. The unsteady forces and moments were computed from the CFD data by integrating the predicted pressure distribution on the body.

The second body modeled was the NAVOCEANO Seahorse AUV. The shape of the body and a subset of the computational grid is shown in Figure 1. The overall body length is 28.46 ft (8.67 m), and the maximum hull diameter is 3.167 ft (0.9652 m). The shroud encloses the propulsor, which includes inlet guide vanes and rotor. The fins have an airfoil-like cross-section and are mounted in an "X" configuration. Those familiar with the vehicle will recognize that the weed-guards have not been modeled. The computational grid for this body is divided into 23 blocks containing a total of approximately 4,800,00 grid points. The maximum and minimum numbers of grid points in a block are approximately 445,000 and 37,000, respectively. In the present study, each of the blade rows are modeled using an appropriate spatially distributed body force. The image in Figure 2 shows the pressure distribution on the afterbody of the Seahorse AUV predicted for one operating condition.

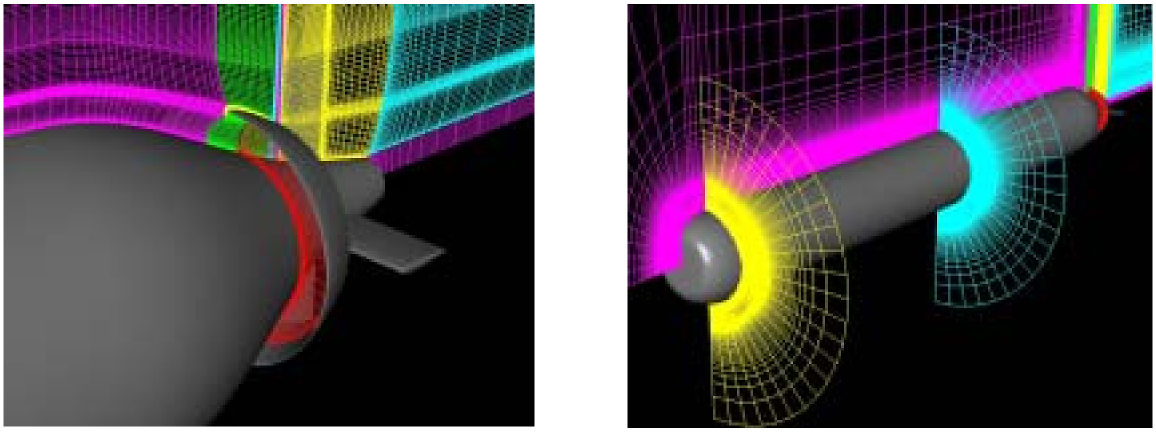

***Figure 1. Seahorse AUV body and subset of computational grid used in UNCLE code*.**

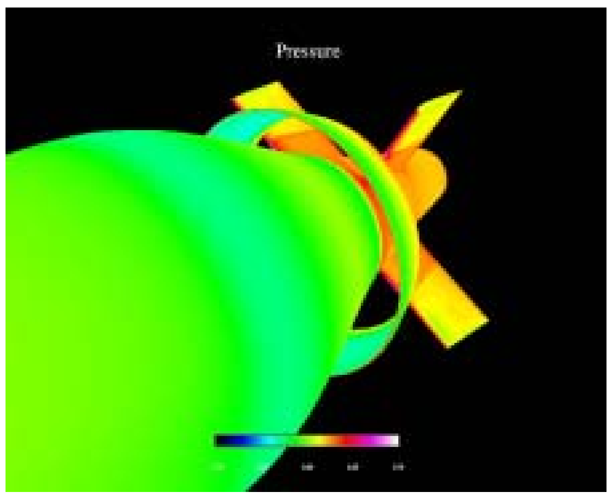

Figure 2. Predicted surface pressure distributions with body forces from propulsor model

RESULTS

The simulations conducted for the SUBOFF body were repeated for the Seahorse AUV model. Predictions for the forces and moments were obtained for steady angle-of-attack cases and for the unsteady plunging motion. Table 1 shows a subset of the linear stability derivatives predicted for the Seahorse AUV. The table shows the name of the non-dimensional coefficient in the first column, the value of the coefficient predicted by CFD calculations in the send column, the estimated value for the coefficient made during vehicle development in the third column, and a coefficient obtained from the analysis of operational data.

Table 1: Seahorse Hydrodynamic Coefficients From Measured and Predicted data.

Coefficient	CFD	Semi-empirical	Experimental
Z'_w	-0.01408	-0.0139	-0.01072
$Z'_{\dot{w}}$	-0.0218	-0.02103	
M'_w	0.00927	0.01248	0.00366
$M'_{\dot{w}}$	-0.00012	-0.000517	
$Z'_{\delta e}$	-0.0108		-0.0089
$Z'_{\delta e}$ and $Z'^{\,3}_{\delta e}$	-0.0063 and –0.2059	-0.0057 and 0.0074	-0.006 and –13.4
$M'_{\delta e}$	-0.0094		-0.0052
$M'_{\delta e}$ and $M'^{\,3}_{\delta e}$	-0.0073 and –0.0952	-0.0034 and –0.0045	-0.0082 and 0.219

Steady-state at AOA=0^o,2.5^o,5^o,10^o,15^o
Steady-state at Fin AOA=0^o,2^o,4^o,6^o,8^o,10^o
Vertical plunge, V_∞=6.5, V_{plunge}=0.025*V_∞

Table 2: Seahorse Hydrodynamic Coefficients From Measured and Predicted data.

Coefficient	CFD	DTRC Experimental Data
Z'_w	-0.0069	-0.0059
$Z'_{\dot{w}}$	-0.0169	-0.0128
M'_w	0.0135	0.0128
$M'_{\dot{w}}$	0.00017	0.0002

Steady-state at AOA=0^o,2.5^o,5^o
Vertical plunge, V_∞=6.5, V_{plunge}=0.025*V_∞

The coefficients Z'_w and M'_w are obtained by plotting steady-state Z (force along vehicle z axis) and M (moment about vehicle y axis), respectively, against the corresponding angles of attack, 0^o,2.5^o,5^o,10^o and 15^o. The slopes of these curves about the origin yield the appropriate coefficients. $Z'_{\dot{w}}$ and $M'_{\dot{w}}$ are obtained from the CFD data for the vertical plunge, unsteady simulation. The raw CFD data is dimensionalized and a least squares fit of Z and M with w and $\dot{w}$, the velocity and acceleration along the vehicle z axis, yields $Z'_{\dot{w}}$ and $M'_{\dot{w}}$ respectively. Alternately, since Z'_w and M'_w are known from the angle of attack CFD cases outlined above, their contributions may be removed from Z and M and a least-squares fit obtained from $\dot{w}$ alone.

The elevator fin coefficients are obtained from the steady state Z and M on the body with the fins deflected at elevator angles of 0^o, 2^o, 4^o, 6^o, 8^o and 10^o. Force and moment contributions from the zero fin deflection, zero angle of attack simulation used above are removed from Z and M to obtain forces and moments on the vehicle due to the fins alone. Z and M are then least square fit with $u^2\delta_e$ and

$u^2\delta_e^{\,3}$ to obtain the fin coefficients. The cubic terms are not accurate since the non-linear contribution of fin forces is apparent at higher fin deflections than those used in the CFD simulation as well as those used to experimentally determine the fin coefficients. It is, however, important to include the cubic term in the fit so as to isolate the linear term from it.

IMPACT/APPLICATIONS

The methodologies developed under this project have the potential to significantly improve the performance and reduce the cost of developing underwater vehicles. In the case of the Seahorse AUV, tow tank testing would have added an additional $300K to the overall cost of the project. The ability to predict the hydrodynamic forces and moments of large AUVs will continue to reduce the development cost of future systems through the elimination of some hydrodynamic testing. The methodologies being developed may contribute significantly to the development of future Navy systems by allowing designers to evaluate a broader range of design alternatives. One area where the methods may find useful application is in high-speed supercavitating vehicles. The operating conditions associated with these vehicles cannot be recreated except during free-running field tests.

TRANSITIONS

The hydrodynamic predictions for the Seahorse AUV have been transitioned to the engineers responsible for the development and maintenance of vehicle control software and simulation capabilities. Results from the analysis of the in-water data and CFD simulations have been used to refine the control system used in-water by the Seahorse AUV.

RELATED PROJECTS

The techniques developed under this project are being applied to the analysis of data obtained during water tunnel testing of a cavity running body. Conventional experimental techniques and analysis methods cannot be applied to the data collected during these tests because a steady operating condition cannot be obtained. Tools that can be applied to obtain model data from large datasets have proven valuable in this project.