Application of Hydrodynamics and Dynamics Models for Efficient Operation of Modular Mini-AUVs in Shallow and Very-Shallow Waters

P. Ananthakrishnan
Department of Ocean Engineering
Florida Atlantic University
777 Glades Road
Boca Raton, FL 33431, USA
phone: (561) 297-3463 fax: (561) 297-3885 email: ananth@oe.fau.edu

Award Number: N000149810151
http://www.oe.fau.edu/~ananth/AUV-Hydro.html

LONG-TERM GOALS

The long-term goal of this research is to contribute to improvements in mechanical design and motion control of autonomous underwater vehicles through rigorous dynamic and hydrodynamic analyses and modeling, particularly for missions in wave-energetic shallow and very-shallow waters.

OBJECTIVES

The objective of the research is to carry out nonlinear dynamics and hydrodynamics analyses of small and modular mini-AUVs and determine the vehicle-stability, -maneuverability and motion-response for a range of missions, vehicle-configurations and sea states, and thereby contribute to improving the efficacy and reliability of modular AUVs.

APPROACH

The research investigates two main aspects pertaining to the motion of autonomous underwater vehicles; *viz, i.* determination of unsteady hydrodynamic forces on an underwater vehicle including the effects of viscosity, large-amplitude body motion and surface waves, and *ii.* analysis of motion response, stability and maneuverability of underwater vehicles subjected to hydrodynamic forces. The hydrodynamic and dynamic simulations are carried out for a range of ambient and vehicle parameters, in order to identify key factors affecting the performance of underwater vehicles.

Robust numerical algorithms and computer programs are specially developed for the analyses. The hydrodynamic forces are computed by solving the governing nonlinear equations using finite-difference and boundary-integral methods. The inviscid nonlinear wave-AUV interaction problem is solved and wave radiation forces determined using a boundary-integral method based on a mixed *Eulerian-Lagrangian* formulation [6][8][10]. The viscous wave-AUV hydrodynamics problem is solved in primitive variables[4] using a boundary-fitted coordinates based finite-difference method [2][3][5] to determine drag, wave-radiation and -diffraction forces. Approximate linear methods, as that based on the *Froude-Krylov* formulation[7][9] are also considered, to determine the diffraction forces of long and small-amplitude waves on small underwater vehicles.

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 **Application of Hydrodynamics and Dynamics Models for Efficient Operation of Modular Mini-AUVs in Shallow and Very-Shallow Waters**	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) **Department of Ocean Engineering,,Florida Atlantic University,777 Glades Road,,Boca Raton,,FL, 33431**	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 goal of this research is to contribute to improvements in mechanical design and motion control of autonomous underwater vehicles through rigorous dynamic and hydrodynamic analyses and modeling, particularly for missions in wave-energetic shallow and very-shallow waters.

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)**	**7**	

The rigid-body equations of AUV motion, subject to hydrodynamic and thruster forces, are solved to determine the *open-loop* vehicle stability, maneuverability and motion response of an AUV for various vehicle configurations and operating conditions[1] . Using the dynamic simulation software developed for the analysis, one can determine optimal configuration of an AUV and viability of a mission in the given sea state *a priori*.

In order to validate and complement the numerical algorithms used for the determination of hydrodynamic forces, model tests are planned at the SeaTech facility of Florida Atlantic University in the recently-completed wave-current tank equipped with PIV and force-measurement systems. Data of vehicle motions and sea states collected during the sea trials of Florida Atlantic University's AUVs conducted in 2000 will be used to assess the predictive capability of the AUV hydrodynamics/dynamics models developed in this research.

Complementing the research on the vehicle dynamics, a hydrodynamics-based algorithm was developed to model the thrust and torque of the AUV propeller. The algorithm is based on the blade-element method with lift and drag coefficients of the blade sections specified from experimental data. The algorithm can be used for the design of optimum AUV thrusters, and also to determine thrust as a function of rpm, pitch angle and vehicle speed, as required in the simulation of vehicle dynamics.

WORK COMPLETED

The efforts performed in fiscal year 2001 (1 October 2000 to 30 September 2001) are as follows:

1. Boundary-integral methods based on the mixed *Eulerian-Lagrangian* formulation[6] for the analysis of nonlinear wave-body interactions and on the simple-source formulation[10] for the analysis in the frequency domain have been developed and the wave hydrodynamic forces determined for the *Morpheus* and *Ocean Explorer* (OEX) AUVs for a range of parameters.

2. A robust finite-difference algorithm has been developed to compute forces due to long waves about underwater vehicles in shallow waters.

3. A fully-implicit three-dimensional finite-difference algorithm has been developed to analyze large Reynolds number flow about underwater vehicles.

4. Wave exciting forces on *Morpheus* AUV heading at various angles, speeds and depths have been computed based on the *Froude-Krylov* method.

5. Data on OEX vehicle motion and propeller performance have been collected from sea trials, which will be used for comparisons with numerical simulations.

6. The wave tank at the FAU's SeaTech facility has been equipped with equipments such as wave-maker, force and wave measurement systems, and PIV appropriate to conduct model tests.

7. The nonlinear stability of *Morpheus* and *Ocean Explorer* AUVs in deep water have been analyzed, by solving fully-nonlinear 6DOF equations of motion, for a range of parameters such as location of center of gravity and fin geometry.

8. The dynamic simulation of vehicle response to surface waves is in progress.

RESULTS

Key results and findings of our efforts during the fiscal year 2001 are dicussed in this section.

Finite-Difference Analysis: Three-dimensional viscous flow results are obtained for uniform and oscillatory flows about underwater vehicles. Fig.1 shows the horizontal component of velocity about a streamlined underwater body (modified double *Wigley* hull) at a Reynolds number of 10^5 . One can clearly observe boundary-layer separation at the aft of the hull and its reattachement downstream in the wake.

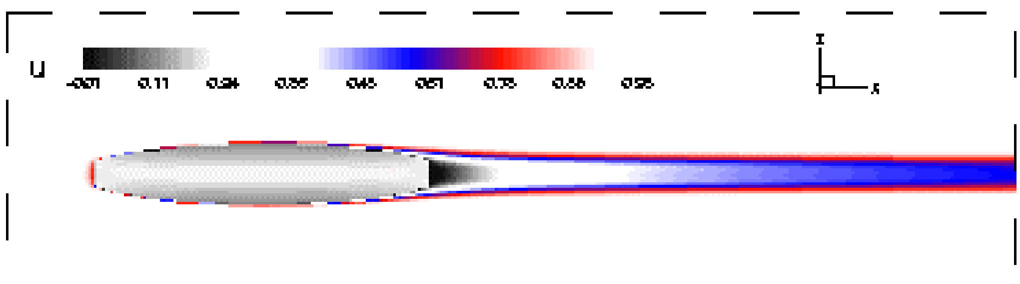

Fig. 1: Horizontal velocity about a streamlined underwater body at Re=10^5

In Fig.2, we present instantaneous axial velocity and streamlines corresponding to an oscillatory flow about a OEX's *Gertler* geometry. From the plot, one can observe the shedding of vortices which then are transported back and forth the body by the oscillating onset flow. An oscillating onset flow is an ideal model of an AUV advancing in long/shallow-water waves, and the present work reveals many interesting hydrodynamic phenomena associated with small submarines operating in littoral waters.

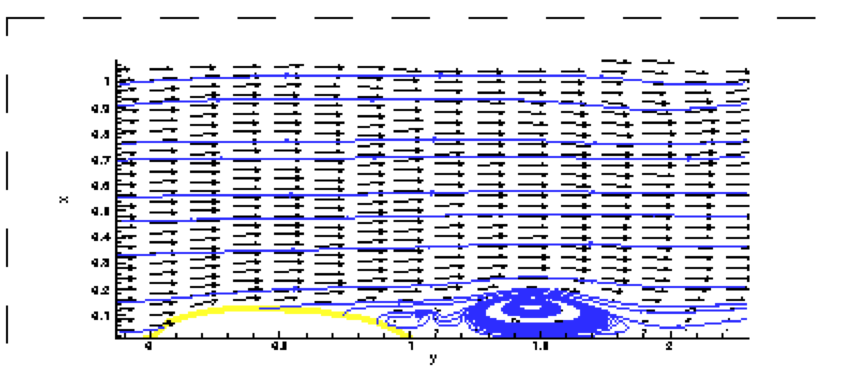

Fig.2: Instantaneous velocity field and streamlines for an AUV advancing in shallow-water waves.

Boundary-Integral Analysis: Using the boundary-element method developed for the research, hydrodynamic forces and coefficients for the *Morpheus* AUV are computed. A typical discretization of the AUV for the analysis is shown in Fig.3, and the velocity field due to motion in deep water in Fig. 4.

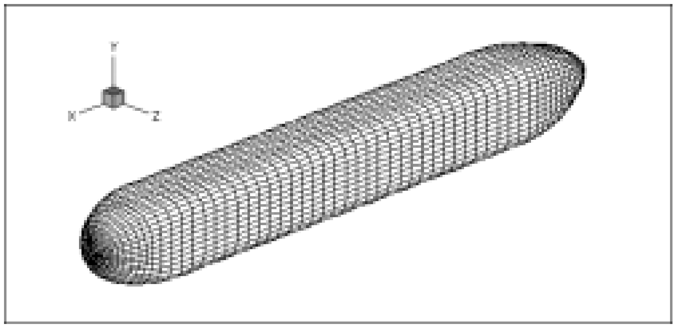

Fig.3: Surface discretization of the Morpheus AUV for boundary-integral analysis.

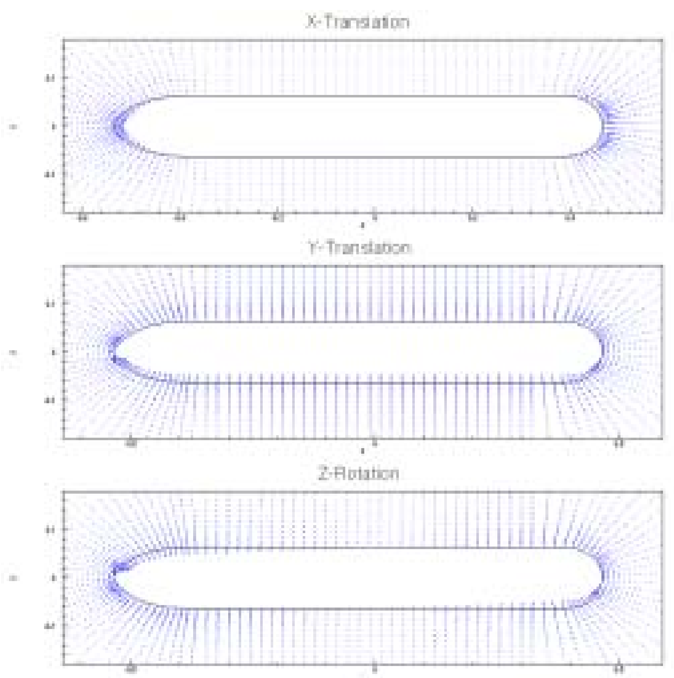

Fig.4: Velocity fields associated with translation and rotation of Morpheus AUV in deep water.

The hydrodynamic forces are computed using the hydrodynamic coefficient per *added-mass theory*[7] . The nonlinear *Morpheus*-wave interactions corresponding to heave, surge and sway motions are computed using the boundary-integral method based on the mixed Eulerian-Lagrangian formulation[6]. The instantaneous free-surface deformations associated with these motions are given in Fig. 5 below.

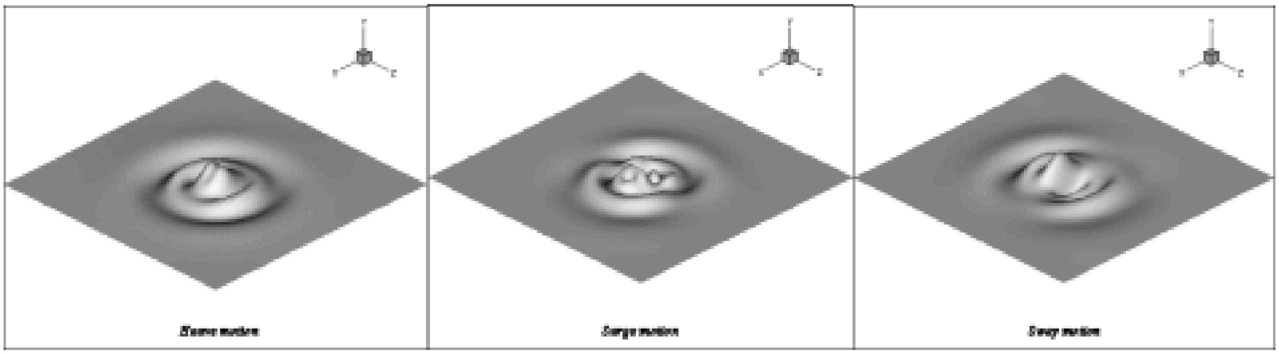

Fig.5: Free-surface deformations corresponding heave(left), surge(middle) and sway(right) oscillations of Morpheus AUV at nondimensional depth 0.75, amplitude of oscillation 0.05.

The figure reveals the radiation of complex wave patterns associated with Morpheus motion near the surface. Hydrodynamic forces (added-mass and wave-damping) are also computed and used to determine motion response of the AUV in waves.

Dynamic Stability Analysis of *OEX* and *Morpheus* AUVs: The unsteady rigid-body motion of AUVs in deepwater is analyzed by solving the *fully nonlinear 6DOF* equations of motion using the finite-difference method. Analytical solutions for the linearized equations are also obtained for validating the numerical algorithm. The hydrodynamic forces acting on the vehicle are determined using the boundary-integral solution and the added-mass theory, as discussed earlier. The forces of control surfaces are modeled using experimental data. Based on the simulations, improvements to vehicle configurations and fin designs are suggested. For example, it is found that the *Morpheus* AUV with four payload modules is directionally more stable than the one with three modules. It is also found that having a hinged-rudder, with larger surface area, will contribute to the improvement of the open-loop stability of the *Morpheus* AUV. The analysis also emphasizes the importance of adding fixed rudders and stern-planes onto small AUVs driven by vectored thrusters for ensuring the directional stability of the vehicle.

IMPACT/APPLICATIONS

1. The hydrodynamic analyses contribute to a better understanding of the fundamental physics of nonlinear wave-body interactions and vehicle dynamics in shallow and very-shallow waters.

2. The nonlinear dynamic simulations of vehicle motions help to identify the key mechanisms affecting the stability of marine vehicles. The analysis thus contributes to the determination of optimal vehicle configurations and the development of efficient controllers for small modular underwater vehicles.

TRANSITIONS

1. The results and findings of the hydrodynamics and rigid-body dynamics analyses are shared with the AUV researcher Dr. Edgar An, Department of Ocean Engineering, Florida Atlantic University who is involved in the development of simulation software and control algorithms for AUVs.

REFERENCES

1. P. Ananthakrishnan and S. Decron, “Dynamics of Small- and Mini-Autonomous Underwater Vehicles: Part I. Analysis and Simulation for Midwater Applications", *Technical Report* , 63p, Department of Ocean Engineering, Florida Atlantic University, 2000

2. P. Ananthakrishnan, “Radiation hydrodynamics of a floating vertical cylinder in a viscous fluid,” *Journal of Engineering Mechanics*, vol. 125, No.7, pp. 836-847, 1999.

3. P. Ananthakrishnan, “Nonlinear diffraction of waves over a submerged body in a real fluid,” *Proceedings of the Eighth International Offshore and Polar Engineering Conference*, vol. III, pp. 288-293, Montreal, 1998.

4. A.J. Chorin, “A numerical method for solving incompressible viscous flow problems,” Journal of Computational Physics, vol. 2, pp. 12-36, 1967.

5. L. Gentaz , P.E. Guillerm, B. Alessandrini, and G. Delhommeau, “Three-dimensional free surface viscous flow around a ship in forced motion,” *Proceedings of the Seventh International Conference on Numerical Ship Hydrodynamics*, Nantes, 1999.

6. M.S. Longuet-Higgins and E.D. Cokelet, “The deformation of steep surface waves on water: I. A numerical method of computation,” *Proceedings of the Royal Society of London*, A 350, pp.1--26, 1976.

7. J.N. Newman, *Marine Hydrodynamics*, MIT Press, Cambridge, MA, 1977.

8. C. Puaut, “Hydrodynamic analysis of underwater vehicles in shallow waters,” *M.S. Thesis,* (advisor: P. Ananthakrishnan) Department of Ocean Engineering, Florida Atlantic University, 2001.

9. J.V. Wehausen, “The motion of floating bodies,” *Annual Review of Fluid Mechanics*, vol. 3, pp. 237-268, 1971.

10. R. W. Yeung, “Numerical methods in free-surface flows,” *Annual Review of Fluid Mechanics*, vol. 14, pp. 395-442, 1982.