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

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LONG-TERM GOALS

The long-term goal of this research is to contribute to improvements in design and motion-control of small autonomous underwater vehicles, including multiple-vehicle operations and particularly for missions in wave-energetic shallow and very-shallow waters, based on rigorous dynamic and hydrodynamic analyses and modeling.

OBJECTIVES

The objective of the research was to carry out nonlinear dynamics and hydrodynamics analyses of small AUVs and determine their stability, maneuverability and seakeeping characteristics for a range of missions, vehicle-configurations and sea states, and thereby contribute to improving the efficacy and reliability in performance of AUVs in littoral waters.

APPROACH

The research has investigated two main aspects of dynamics and hydrodynamics of underwater vehicles; namely*,* (i) determination of wave-diffraction and -radiation forces on an underwater vehicle including effects of viscosity, large-amplitude body motion and surface waves, and (ii) analysis of motion response, stability and maneuverability of underwater vehicles subjected to the hydrodynamic forces. The hydrodynamic and dynamic simulations have been carried out for a range of ambient and vehicle parameters, in order to identify key factors affecting the performance of underwater vehicles.

Computationally efficient and robust algorithms have been developed in-house for the present analyses. The hydrodynamic forces were computed by solving the governing nonlinear equations using finite-difference [2] and boundary-integral methods [6][7][8]. The inviscid nonlinear wave-AUV interaction problem was solved and wave-radiation and -diffraction forces determined using a boundary-integral method based on the mixed *Eulerian-Lagrangian* formulation [3]. As, in the regimes of their validity, the linear and inviscid calculations are straightforward and economical, boundary integral methods based on simple source distribution and linearized boundary conditions [10] have also been developed. Approximate methods, such as the *Froude-Krylov* method [5][9], are also considered to determine the diffraction forces due to long and small-amplitude waves on small underwater vehicles.

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14. ABSTRACT
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15. SUBJECT TERMS

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The viscous wave-AUV hydrodynamics problem, *ie.,* Navier-Stokes equations together with viscous free-surface conditions, was solved in primitive variable using boundary-fitted coordinates based finite-difference method [2] to determine drag, and radiation- and diffraction-forces including effects of viscosity. Turbulence models, such as Baldwin-Lomax, were also considered for the solution of Reynolds-Averaged Navier-Stokes equations.

The rigid-body equations of AUV motion, subject to hydrodynamic and propulsion forces, were solved to determine the open-loop vehicle stability, maneuverability and motion response for various vehicle configurations and operating conditions [1] [7]. In these simulations, the hydrodynamic forces are represented in the form of coefficients. Numerical simulations corresponding to rotating-arm and planar oscillation tests [4] were conducted to determine the hydrodynamic coefficients including surface wave effects [7]. Open loop responses of deeply-submerged and near-surface AUVs were compared, to determine the effect of a free surface on vehicle stability [7]. Based on the software developed for the analysis, optimal configuration of an AUV and viability of a mission in a given sea state can be determined *a priori.*

Complementing the proposed research on the vehicle dynamics, a simple 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 thrusters for the AUV and to determine thrust and torque as functions of rpm, pitch angle and forward speed.

WORK COMPLETED

The efforts performed are as follows:

- Computationally-efficient boundary integral algorithms, specifically in terms of iterative solvers and modeling of open boundary using damping layer, were developed for fully nonlinear analysis of AUV and wave interactions [7][8].
- A fully-implicit three-dimensional finite-difference algorithm has been developed to analyze viscous flow about underwater vehicles and to determine the hydrodynamic forces.
- Linear and nonlinear wave diffraction forces were computed for the Ocean Explorer (OEX) AUV for a range of paramaters [8].
- Hydrodynamic coefficients (stability derivatives), including free surface effects, were computed for the OEX vehicle [7].
- Dynamic stability analyses were conducted for OEX AUV operating in deep waters and near a free surface, in order to determine the stabilizing effect of a free surface on a submerged vehicle [7].
- The Baldwin-Lomax turbulence model has been implemented in the viscous-flow solver and preliminary turbulent flow results obtained. A robust grid-generation algorithm based on an solution-adaptive technique has been developed. Viscous flow results corresponding to OEX vehicle operating in shallow-water wave field have been obtained.

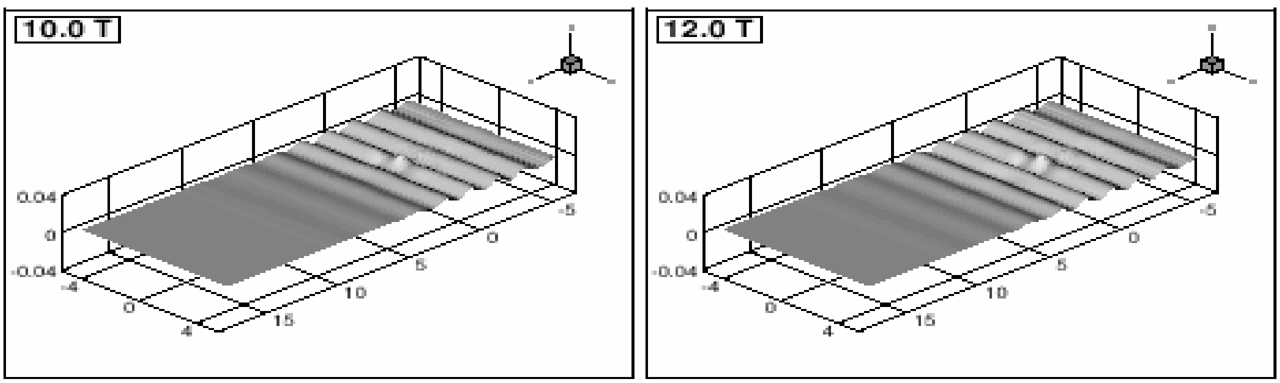
RESULTS

A few representative results, significant findings and new capabilities developed in our FY03 research are listed below:

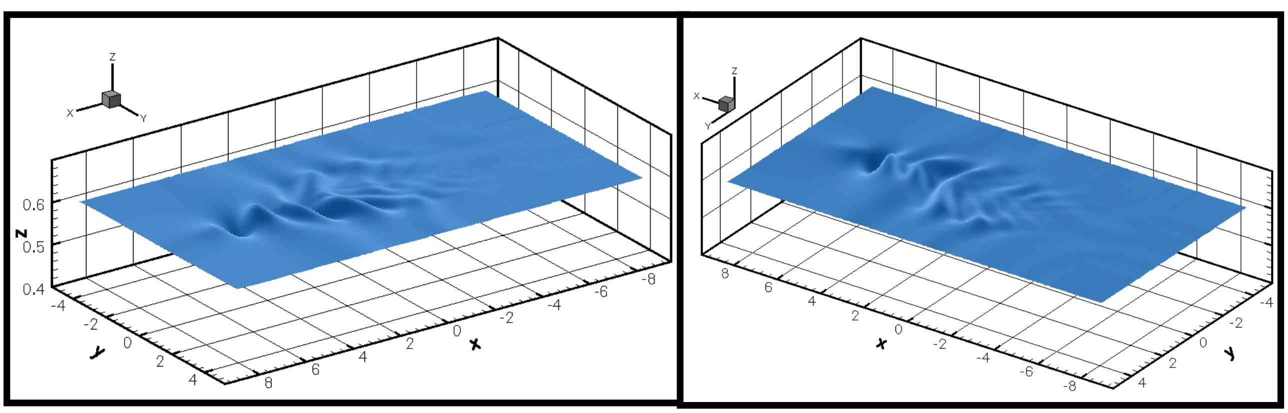
1. A computationally-efficient three-dimensional nonlinear numerical wave tank was developed to study diffraction of waves over submerged vehicle [8] (Fig. 1). Damping layers to model open down-stream boundary and iterative matrix solvers are some salient features of the model. Using the numerical wave tank, one can efficiently and economically determine diffraction forces on submerged AUVs.

2. Wave diffraction forces on the OEX vehicle were computed for a range of parameters [8]. The key findings of the research, which include the parameters governing the significance of nonlinearity, are summarized in the thesis [8].

3. Wave radiation forces and hydrodynamic coefficients for horizontal plane motion of OEX vehicle in shallow waters were computed, by simulating standard maneuvering tests such as the rotating arm and planar oscillation tests [7] (Fig. 2). The significance of the methodology and algorithm is that it could save thousands of dollars which otherwise must be spent in conducting model basin tests to determine the hydrodynamic coefficients and stability derivatives of underwater vehicles.



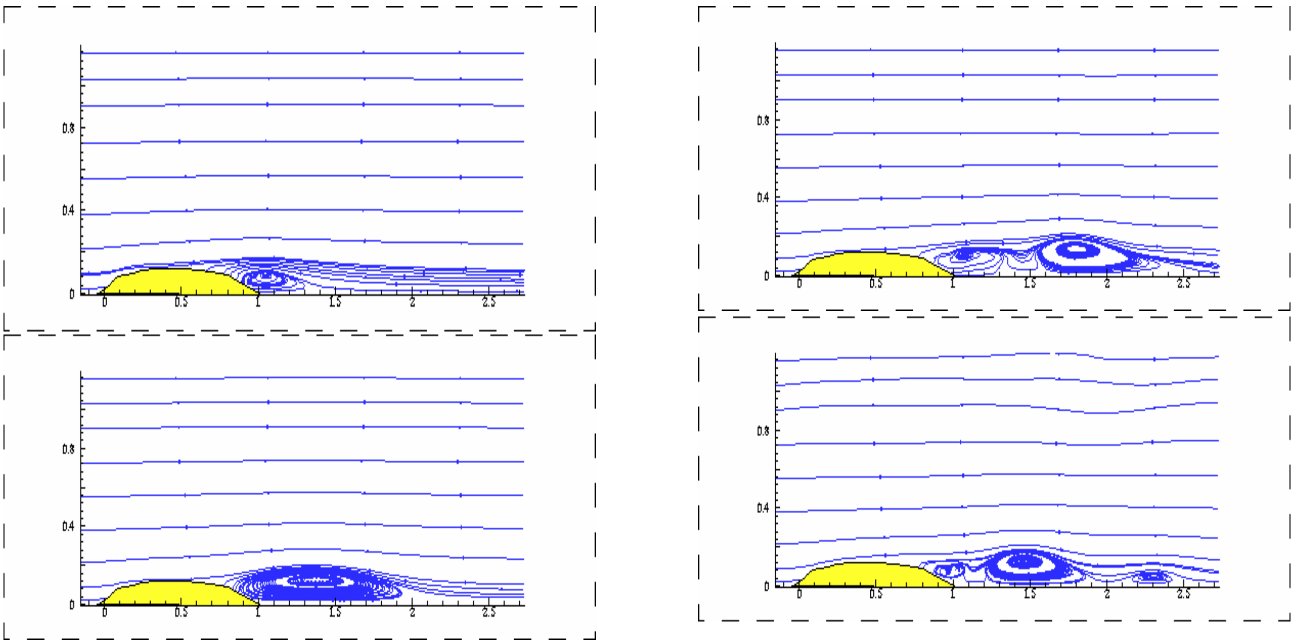
<u>Fig. 1</u>: Generation and propagation of waves in the numerical wave tank developed for the study of wave diffraction over an AUV [8]



<u>Fig. 2</u>: Wave generation in the numerical simulation of planar oscillation tests to determine hydrodynamiccoefficients governing the directional stability of near-surface AUVs [7]

4. Wave forces on an OEX vehicle advancing in shallow water waves, including effects of viscosity, were computed using a sophisticated finite-difference algorithm [2]. The new results shed light on the

effects of surface waves on the inception and evolution of wake vortices, and thus on the pressure field and drag forces, of the vehicle (Fig. 3):



<u>Fig. 3</u>: Instantaneous streamlines on the starboard side of OEX AUV advancing in shallow water waves.

The details of the significance of the present research, both in terms of the development of new computational tools and capabilities and new findings on AUV hydrodynamics, are given in the cited references and in the manuscripts in preparation for publication in the journals.

IMPACT/APPLICATIONS

The research as conducted by the PI and his students is unique in its kind in that it has examined the dynamics and hydrodynamics of the underwater vehicle based on a rigorous analysis including effects of surface waves and viscosity. The algorithms and methodolgies developed could (i) effectively replace or minimalize the use of towing tanks and model basins to determine hydrodynamics characteristics, (ii) contribute to the improvement of AUV design from hydrodynamics viewpoint and (iii) be used to determine the viability of a mission *a priori*. Our research has also contributed to the basic science of marine hydrodynamics in the following ways.

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

2. The nonlinear dynamic simulations of vehicle motions help to identify the key mechanisms affecting and contributing to marine-vehicle stability. The results have shed light on the stabilizing effect of a free surface on the directional stability of a near-surface AUV.

3. The research has also contributed to identifying effects of surface waves and viscosity on the hydrodynamic coefficients of underwater vehicles.

4. The research has led to the development of accurate boundary-integral and finite-difference methods for the solution of fully nonlinear wave-vehicle interaction problems.

TRANSITIONS

In order to extend the methodologies and algorithms, successfully developed for the hydrodynamics and dynamics of AUVs, to surface ships and thereby contribute to the design and control of fast multi-hull ships, the PI has recently submitted a proposal to the ONR's BAA03-013.

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PUBLICATIONS

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2. V. Vinayan, "Boundary-integral analysis of nonlinear diffraction forces on a submerged body," *M.S. Thesis,* (advisor: Dr. P. Ananthakrishnan) Department of Ocean Engineering, Florida Atlantic University, August 2003.