Hydromechanics Laboratory

Professor Gregory J. White
Director

The Naval Academy Hydromechanics Laboratory (NAHL) is a unique facility among universities in the United States that has served the needs of the midshipmen, faculty, and the Navy for more than 27 years. The facility supports midshipmen courses and research, faculty research, and special projects for the U.S. Navy and Coast Guard in the areas of naval architecture and ocean engineering. What makes the NAHL unique is the combination of testing facilities available for student and faculty use. A large towing tank (380-foot x 26-foot x 16-foot) and a small towing tank (120-foot x 8-foot x 5-foot), both fitted with wave-makers, provide a wide range of capabilities including opportunities to evaluate scaling effects. The other major facilities in the Lab include a coastal engineering wave basin (52-foot x 44-foot x 2-foot), a small wave tank with a sand beach (39-foot x 4-foot x 2-foot), a circulating water channel (16-inch x 16-inch x 4-foot test section), and a stability and ballasting tank.

The laboratory facilities are used on a weekly-basis by midshipmen in the Naval Architecture and Ocean Engineering majors, and are used each semester by midshipmen in Mechanical Engineering, Electrical Engineering, and Oceanography majors. In addition, more than 600 midshipmen use the facility for a number of laboratory classes each year as part of EN200, a core-engineering course taken by all midshipmen in non-engineering majors. As a result, nearly all midshipmen use the NAHL facilities at some point during their education at the Naval Academy.

At the start of the fall semester, the Hydromechanics Laboratory had almost completely recovered from the effects of Tropical Storm Isabel. The 120-foot towing tank had been complexly renovated and both the wavemaker and towing carriage were operating at levels better than before the flood. The new control software for both systems gave us more flexibility and control than ever before. The coastal basin and sediment flume tank wavemakers were both in operation. The 380-foot tank wavemaker had undergone extensive repair and was operational, though with somewhat limited capabilities. Work was still in progress on the 380-foot tank towing carriage. This left the Hydromechanics lab in a position where it could support all of the labs for EN200, EN342, EN420, SO430, and some of the labs for EN455. We also supported two midshipmen independent research projects and two faculty research projects.

Before the end of the fall semester, the 380-foot tank towing carriage came back on line and we were able to do the first laboratory experiments in that facility in two years. EN455 used the Large Amplitude Planar Motion Mechanism (LAPPM) in a series of experiments near the end of the semester. Over the intercessional period between academic semesters, the Hydrodynamics Laboratory stayed extremely busy. A research project in the 380-foot tank using a staff-developed towing rig for small bodies provided the Naval Undersea Warfare Center (NUWC) Newport, RI with data needed to fast track an important new torpedo counter device. Work through the holidays finally brought to a close a submarine resistance project for the Office of Naval Intelligence that had been in progress when Tropical Storm Isabel struck the Chesapeake Bay and the Naval Academy.

During the spring semester of 2006, the Hydromechanics Laboratory was back in full operation. The Lab was able to fully support the course work in EN458, EN353, EN246, EN200, EN462, EN475, EN486D, EM324 and EM318. This support ranged from performing one or two lab demonstrations (EM318 and EM324) to performing fourteen extensive laboratory experiments (EN458). A record of nine midshipman independent research projects and nine student design projects were also conducted in the NAHL during the spring semester.

In addition to classroom support, the NAHL facilities are used by midshipmen, faculty, and NAHL staff for both fundamental and applied research. During the past year, research programs conducted in the laboratory have included:

- *FAST AUV, Phase I* (Sponsor: Naval Undersea Warfare Center Newport)
- *FAST AUV, Phase II* (Sponsor: Naval Undersea Warfare Center Newport)
- *Experimental Investigation of Forces and Moments on a Submarine Shape Operating in the Vicinity of the Bottom* (Sponsor: Naval Air Systems Command Orlando TSD)
- *Comparative Analysis of Submarine Sails* (Sponsor: Hydromechanics Laboratory)
- *Preliminary Data Report on Resistance Tests of the Maritime Applied Physics Corporation (MAPC) Monocat* (Sponsor: Naval Surface Warfare Center Carderock)
- *Preliminary Data Report on Resistance Tests of the Bath Iron Works (BIW) Catamaran* (Sponsor: Naval Surface Warfare Center Carderock)
- *Preliminary Data Report on Resistance Tests of the of the MAPC Swathcat* (Sponsor: Naval Surface Warfare Center Carderock)
- *Demi-Hull Experiment Results* (Sponsor: Naval Surface Warfare Center Carderock)
- *Preliminary Data Report on Resistance Tests of the BIW Trimaran* (Sponsor: Naval Undersea Warfare Center Carderock)
- *Mooring Loads due by Passing Vessels* (Sponsor: Naval Facilities Service Center)
- *Comparison of the Hydrodynamic Performance of Fouling-Release Surfaces with Copper-Based Antifouling Coatings* (Sponsor: Office of Naval Research)
- *Surface Roughness Effects on Drag and Turbulent Boundary Layer Structure* (Sponsor: Office of Naval Research)
- *Resistance, Seakeeping and Maneuvering Model Tests on a Mobile Landing Platform Ship* (Sponsor: Naval Surface Warfare Center Carderock)

The Hydromechanics Laboratory is operated and maintained by a multi-talented staff, which includes three engineers/naval architects, two engineering technicians, and an office manager/secretary. Supporting laboratory efforts are the shop and model-making facilities in the Technical Support Department. The laboratory is further supported by a Memorandum of Understanding (MOU) with the Naval Station-Annapolis, providing support of diving operations in the laboratory.

The results of laboratory research efforts are reflected in journal articles written by faculty and laboratory staff members and in presentations at technical symposia. The Laboratory is actively represented in the International Towing Tank Conference (ITTC) and staff members are active participants in the Society of Naval Architects and Marine Engineers (SNAME), the American Society of Naval Engineers (ASNE), the Chesapeake Sailing Yacht Symposium (CSYS), the American Towing Tank Conference (ATTC), and the Coasts, Oceans, Ports and Rivers Institute (COPRI) of the American Society of Civil Engineers (ASCE). The diverse interests of these organizations reflect the broad nature of the Hydromechanics Laboratory's activities.

Sponsored Research

FAST AUV, Phase I

Researcher: Mr. William E. Beaver, Naval Architect, P.E., Hydromechanics Laboratory
Sponsor: Naval Undersea Warfare Center (NUWC) Newport

The United States Naval Academy Hydromechanics Laboratory constructed a model of a FAST AUV (autonomous underwater vehicle) incorporating new fore body geometry. The drag of this model was determined using a simple string tow apparatus for two ballast conditions.

FAST AUV Phase II

Researcher: Mr. William E. Beaver, Naval Architect, P.E., Hydromechanics Laboratory
Sponsor: Naval Undersea Warfare Center (NUWC) Newport

The Hydromechanics Laboratory developed a dynamometer to measure drag, heave forces, and pitching moments on a constrained model of a FAST AUV (autonomous underwater vehicle). A hydrodynamic assessment of the baseline configuration and several geometry variations were performed. The impact of an elliptic bow, a towed array, and three tail cone fin configurations were investigated. Work was also conducted to characterize the performance of stock propeller for the FAST AUV to assist in preparing powering estimates.

Preliminary Data Report on Resistance Tests of the Maritime Applied Physics Corporation (MAPC) Monocat

Researcher: Mr. William E. Beaver, Naval Architect, P.E., Hydromechanics Laboratory
Sponsor: Naval Surface Warfare Center (NSWC) Carderock

Resistance experiments were conducted at two displacements for a 1 to 150 scale model of the MAPC/BIW (Maritime Applied Physics Corporation/Bath Iron Works) Monocat. Measured resistance, heave and trim data is presented. The full scale powering is estimated based on a simple extrapolation technique.

Preliminary Data Report on Resistance Tests of the Bath Iron Works (BIW) Catamaran

Researcher: Mr. William E. Beaver, Naval Architect, P.E., Hydromechanics Laboratory
Sponsor: Naval Surface Warfare Center (NSWC) Carderock

Resistance experiments were conducted at two displacements for a 1 to 140 scale model of the BIW (Bath Iron Works) Catamaran. Measured resistance, heave and trim data are presented. The full scale powering was estimated based on a simple extrapolation technique.

Demi-Hull Experiment Results for the Bath Iron Works (BIW) Catamaran

Researcher: Mr. William E. Beaver, Naval Architect, P.E., Hydromechanics Laboratory
Sponsor: Naval Surface Warfare Center (NSWC) Carderock

Resistance tests on a single demi-hull of the BIW (Bath Iron Works) Catamaran were conducted to asses the interference drag associated with the catamaran configuration. The demi hull was run alone and in the catamaran configuration at several hull separation ratios. Measured resistance, heave and trim data are presented. The full scale powering performance was estimated based on a simple extrapolation technique.

Preliminary Data Report on Resistance Tests of the Maritime Applied Physics Corporation (MAPC) Swathcat

Researcher: Mr. William E. Beaver, Naval Architect, P.E., Hydromechanics Laboratory
Sponsor: Naval Surface Warfare Center (NSWC) Carderock

Resistance experiments were conducted at two displacements for a 1 to 140 scale model of the MAPC (Maritime Applied Physics Corporation) Swathcat. Measured resistance, heave and trim data are presented. Demi-hull tests at the heavy displacement were conducted to assess interaction drag of the catamaran configuration. The full scale powering performance was estimated based on a simple extrapolation technique.

Preliminary Data Report on Resistance Tests of the Bath Iron Works (BIW) Trimaran

Researcher: Mr. William E. Beaver, Naval Architect, P.E., Hydromechanics Laboratory
Sponsor: Naval Undersea Warfare Center (NUWC) Carderock

Resistance experiments were conducted at two displacements for a 1 to 140 scale model of the Bath Iron Works (BIW) Trimaran. Measured resistance, heave and trim data are presented. Tests on a single hull at the heavy displacement were conducted to assess interaction drag of the trimaran configuration. The full scale powering performance was estimated based on a simple extrapolation technique.

Mooring Forces Induced by Passing Ships

Researcher: Professor David L. Kriebel, Naval Architecture and Ocean Engineering Department
Sponsor: Naval Facilities Engineering Service Center (NAVFAC)

The Navy has recently been experiencing damages to moored ships and piers as a result of excessive motions of the moored vessel caused by passing ship traffic. Many Navy piers are located alongside commercial navigation channels where commercial vessels enter/exit port at a high rate of speed. The waves generated by these vessels may then induce large surge, sway, or yaw motions of any vessels moored at the pier. In order to better understand this problem, a series of physical model tests are being conducted in the Hydromechanics Laboratory. In these tests, one ship model will be moored using load cells while another ship model will be towed past at various speeds and separation distances. Data will be analyzed to develop empirical guidelines on the surge force, sway forces, and yaw moments experienced acting on the moored vessel. Results will also be used to validate computer codes used by the NAVFAC.

Effective Horsepower, Seakeeping, and Maneuvering Tests on a Mobile Landing Platform (MLP) Model

Researcher: Professor Bruce C. Nehrling, Naval Architecture and Ocean Engineering Department
and Mr. John J. Zseleczky, Naval Architect, P.E., Hydromechanics Laboratory
Sponsor: Naval Surface Weapons Center (NSWC) Carderock

During May and June of 2006, the Naval Academy Hydromechanics Laboratory (NAHL) conducted hydrodynamic model tests on a concept hull form of a Mobile Landing Platform (MLP). The MLP is a key component of the Maritime Pre-positioning Force (Future) squadron. It is envisioned to be a mobile "pier in the ocean", capable of conducting vehicle, supply, and troop transfers with a wide range of other surface ships and vehicles while underway in the open ocean. The MLP's primary operational modes will be a relatively high speed transit condition at a draft of approximately 8 meters and a low speed cargo transfer condition at a draft of approximately 13 meters. Based on its mission requirements the MLP will be a large ship (239 meter length on waterline) with some hull parameters falling outside current norms. The objective of the experimental tests conducted by the NAHL on this unique hull form was to provide the Naval Sea Systems Command (NAVSEA) MLP design team with technical information on this hull's powering, seakeeping, and maneuvering characteristics. Powering measurements consisted of bare-hull effective horsepower tests over a range of speeds. Seakeeping tests were conducted in seven different scaled irregular seaways ranging from Sea State 4 to 7. Stability derivatives and basic maneuvering coefficients were obtained by running captive motion tests using the NAHL planar motion mechanism on the unpropelled hull.

Comparison of the Hydrodynamic Performance of Fouling-Release Surfaces with Copper-Based Antifouling Coatings

Researcher: Associate Professor Michael P. Schultz, Naval Architecture and Ocean Engineering Department
Sponsor: Office of Naval Research (ONR)

The primary purpose of a ship antifouling system is to limit the increase in drag that will be incurred with fouling settlement on the hull. Ineffectiveness in this endeavor will lead to an increase in energy consumption and a platform that is unable to meet its mission. The introduction of non-toxic, fouling-release coating systems as alternatives to traditional biocide-based antifoulings has necessitated a change in philosophy with respect to these coatings. Since fouling-release coatings do not prevent settlement, various methods to quantify the tenacity of adhesion of organisms on these systems have been offered. Among these are the hard fouling adhesion test, the water jet cleaning method, the towed foil technique, and the turbulent channel flow apparatus. Data from these tests are of particular interest because fouling-release surfaces that cannot "self clean" due to hydrodynamic forces or be mechanically cleaned without significant damage will likely suffer large drag penalties. For these systems to serve as viable alternatives to traditional biocide-based systems, their hydrodynamic performance must compare favorably with traditional systems over the entire coating life cycle. At present, the data from which to make these fundamental comparisons are not available. The goal of the research is to compare the hydrodynamic performance of the fouling-release coating systems and traditional copper-based systems in the unfouled, fouled, and cleaned conditions over several cleaning cycles and several years' exposure.

Surface Roughness Effects on Drag and Turbulent Boundary Layer Structure

Researcher: Associate Professor Michael P. Schultz, Naval Architecture and Ocean Engineering Department
and Professor Karen A. Flack, Mechanical Engineering Department
Sponsor: Office of Naval Research (ONR)

In turbulence research, a great deal of attention has been given to the "canonical" smooth wall, zero pressure gradient boundary layer. Smooth wall boundary layer studies far outnumber rough wall studies. While the smooth wall studies have provided a basis of understanding turbulent wall flows, in most engineering applications, surface roughness is present (i.e. ship hulls, atmospheric boundary layers, turbomachinery). It is, therefore, of interest to gain a better physical understanding of these flows. The goal of the present research is to do this by documenting fully-developed turbulent boundary layers on a range of rough surfaces. From this, the similarity of both the mean velocity and turbulence structure on rough and smooth walls can be critically evaluated.

Experimental Investigation of Forces and Moments on a Submarine Shape Operating in the Vicinity of the Bottom

Researcher: Commander Jeffery W. Stettler, USN, Naval Architecture and Ocean Engineering Department
Sponsor: Naval Air Systems Command, Orlando Technical Support Division

This report provides results of a test program which has investigated the forces and moments on a generic submarine shape (Series 58 hull form) operating in the vicinity of a smooth bottom. The test results demonstrate the strong "suction" force on a submarine operating in the vicinity of the bottom. This "suction" force draws the submarine toward the bottom, and increases monotonically with both velocity and altitude. When this "suction" force is nondimensionalized (by the velocity squared), it becomes nearly constant at each altitude, increasing monotonically (roughly quadratically) as the altitude decreases (i.e. as the submarine approaches the bottom). This suggests a simple mathematical means for quantifying this "suction" effect for submarine simulators.

The test results also demonstrate only small changes in pitch moment and axial force (resistance) as altitude decreases. The slight increase in resistance near the bottom at higher speeds is consistent with an expected increase in the frictional component of resistance due to the increased relative velocity along the bottom of the hull as the submarine moves near the bottom.

A brief investigation is also made as to the effect of static pitch angle (submarine trim) on the "suction" force. The results demonstrate a general symmetry in "lift" force and pitch moment between the mid-tank results

(far from the bottom) and the near-bottom results. There is little impact of the altitude on the magnitudes of the forces for the same static pitch angle. It is also noted that even one full degree upward pitch angle is insufficient to overcome the bottom "suction" effect. It could be extrapolated that it would probably require two full degrees of upward pitch angle to overcome the bottom "suction" effect.

Independent Research

Comparative Analysis of Submarine Sails

Researcher: Professor Gregory J. White, Naval Architecture and Ocean Engineering Department
Mr. William E. Beaver, Naval Architect, P.E., Hydromechanics Laboratory and Ensign Paul Haagenson, USN
Sponsor: Naval Academy Hydromechanics Laboratory (NAHL)

The objective of the project was to perform a comparative experimental hydrodynamic analysis of two submarine sail configurations and then rank the sail configurations on the basis of the drag and flow characteristics. The experiments were to be performed in the Naval Academy Hydromechanics Laboratory's (NAHL's) 380-foot towing tank using the 13-foot SUBOFF model for the baseline hull. The model testing began in August of 2003 with system calibration and testing of the baseline hull and a baseline generic sail. Those tests were completed in August. Testing on the two sail variants was underway when Tropical Storm Isabel arrived. The flooding from the storm surge associated with Isabel severally damaged all of the NAHL facilities and made further testing impossible. In November of 2005, the 380-foot towing tank at the NAHL once again became fully operational. The models of the two sail configurations were repaired and updated (they had been damaged in the flood). The SUBOFF model and towing sting were also refurbished. The plan was completed during the last weeks of December 2005.

The test matrix consisted of runs made at speeds ranging from 2 fps to 13 fps for the bare hull, the two sail configurations. A total of 89 model runs were made to cover the test matrix and include repeat runs for determining testing precision and repeatability from day to day. Based on the results it is clear that the additional volume in the second sail came at the cost of additional wetted surface. Even a somewhat improved foil shape could not offset the increased frictional drag. However, it should be noted that the increase in drag was consistently on the order of 2 – 3%.

Trident Scholar Project

Design and Implementation of an Autonomous Surface Vessel (Trident Report # 346)

Researcher: Midshipmen 1/C Caleb M. Reed, USN
Advisers: Associate Professor Bradley E. Bishop, Weapons and Systems Engineering Department
and Associate Professor Jennifer K. Waters, Naval Architecture and Ocean Engineering Department
Sponsor: Office of Naval Research (ONR)

Autonomous vehicles are only beginning to make the impact that they soon will have in a variety of applications. Research is ongoing to provide unmanned vehicles with higher cognitive abilities in order to simplify or eliminate the role of an operator. Advancing the understanding and development of Autonomous Surface Vessels (ASVs), the objective of this research project, will be beneficial to not only the military, but also in many commercial and research applications.

Multiple criteria were considered in selecting the type of vessel and maneuvering hardware most appropriate for the desired applications. A semi-planing monohull with an electric motor and single rudder was selected as the test bed for this research.

In addition, sensors were chosen to provide the necessary data for an autonomous controller. These sensors were integrated onto a single circuit board which included a dedicated microprocessor for their operation and

control. Different communication techniques were investigated to allow the primary microprocessor to pass information to a secondary microprocessor which produced the output for the control motors.

Techniques for mathematically modeling the vessel were investigated, and physical experiments were conducted to determine the maneuvering parameters of the vessel, required for the model's development. From this model, a control system was developed to guide the vessel to a desired position following waypoints based on the input of the sensors. These waypoints were automatically determined from information stored on an off-board computer. Data was collected in order to improve the functionality of the sensors and navigational techniques.

During this research, numerous challenges specific to small, low-cost ASVs were encountered and investigated. In the end, a fully functional low-speed miniature ASV was developed and tested in the waters surrounding the United States Naval Academy. This platform represents an important step forward in autonomous marine surface vessels.

Journal (Refereed) Manuscripts

CONNELLY, J.S., Ensign USN, SCHULTZ, M.P., Associate Professor, and FLACK, K.A., Professor, "Velocity-Defect Scaling for Turbulent Boundary Layers with a Range of Relative Roughness," *Experiments in Fluids*, Vol. 40, 2006, pp. 188-195.

> Velocity profile measurements in zero pressure gradient, turbulent boundary layer flow were made on a smooth wall and on two types of rough walls with a wide range of roughness heights. The ratio of the boundary layer thickness (δ) to the roughness height (k) was $16 \leq \delta/k \leq 110$ in the present study, while the ratio of δ to the equivalent sand roughness height (k_s) ranged from $6 \leq \delta/k_s \leq 91$. The results show that the mean velocity profiles for all the test surfaces agree within experimental uncertainty in velocity-defect form in the overlap and outer layer when normalized by the friction velocity obtained using two different methods. The velocity-defect profiles also agree when normalized with the velocity scale proposed by Zagarola & Smits (1998). The results provide evidence that roughness effects on the mean flow are confined to the inner layer, and outer layer similarity of the mean velocity profile applies even for relatively large roughness.

FLACK, K.A., Professor, SCHULTZ, M.P., Associate Professor, SHAPIRO, T.A., Ensign USN, "Experimental Support for Townsend's Reynolds Number Similarity Hypothesis on Rough Walls," *Physics of Fluids*, Vol. 17, Article # 035102, (2005).

> The Reynolds number similarity hypothesis of Townsend states that the turbulence beyond a few roughness heights from the wall is independent of the surface condition. The underlying assumption is that the boundary layer thickness (δ) is large compared to the roughness height (k). This hypothesis was tested experimentally on two types of three-dimensional, rough surfaces. Boundary layer measurements were made on flat plates covered with sandgrain and woven mesh roughness in a closed return water tunnel at a momentum thickness Reynolds number (Re_θ) of ~14000. The boundary layers on the rough walls were in the fully rough flow regime ($k_s^+ \geq 100$) with the ratio of the boundary layer thickness to the equivalent sand roughness height, δ/k_s, greater than 40. The results show that the mean velocity profiles for rough and smooth walls collapse well in velocity defect form in the overlap and outer regions of the boundary layer. The Reynolds stresses for the two rough surfaces agree well throughout most of the boundary layer and collapse with smooth wall results outside of $3k_s$. Higher moment turbulence statistics and quadrant analysis also indicate the differences in the rough wall boundary layers are confined to $y < 5k_s$. The present results provide support for Townsend's Reynolds number similarity hypothesis for uniform three-dimensional roughness in flows where $\delta/k_s \geq 40$.

Conference Proceedings

WALLENDORF, L. A., Ocean Engineer, P.E., Hydromechanics Laboratory, (co-editor), "Solutions to Coastal Disasters", *2005 Conference Proceedings*, Reston, VA: American Society of Civil Engineers, ISBN: 0-7844-0774-6.

> Publication contains 80 papers that focus on the science and research tools, management procedures, and engineering and planning solutions that are explored and used during coastal disasters. Coastal engineers, planners, managers, scientists, geologists, economists, oceanographers and meteorologists present information useful for a multi-disciplinary audience. Case studies for coastal disaster events occurring through November 2004 are presented. The effects of hurricanes on the United State's coastlines on the Gulf of Mexico and the Atlantic Ocean are a major focus of this research, and this investigation includes the four major hurricanes of 2004 and Tropical Storm Isabel in 2003. Other coastlines discussed include Lake Ontario (Canada), the North Sea (Denmark, Germany, Netherlands, and United Kingdom), the Pacific Ocean (California, Hawaii, Korea, Japan and New Zealand) and the Indian Ocean (Bangladesh, India).