

# **A PRACTICAL HYDRODYNAMIC-BASED MODEL OF AUV THRUSTER DYNAMICS FOR USE IN CLOSED-LOOP CONTROL OF VEHICLE MOTIONS**

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## **LONG-TERM GOALS**

The long-term objective of this research program is to improve the automatic control of autonomous underwater vehicles (AUV) through the incorporation of thruster hydrodynamics into control algorithms.

## **OBJECTIVES**

The scientific and technical objectives of this research are to develop an accurate hydrodynamic model of an AUV thruster, incorporate the model into a vehicle control system, and demonstrate accurate closed-loop thruster control in unsteady conditions. Previous, research on propeller modeling has centered almost exclusively on in-flows that are steady in time but vary spatially. This research focuses on the temporally varying hydrodynamics caused by changes in the thruster's angular velocity. These conditions are typical of an underwater vehicle that is maneuvering or holding position in a current.

## **APPROACH**

The hydrodynamic model will be developed through a combination of numerical simulations and experimental measurements under steady and unsteady operating conditions.

The experiments will be conducted in a flume and consist of measuring the thrust, torque, and flow field as a function of propeller angular velocity. The tests will involve mounting an AUV thruster unit (motor and propeller) on a test stand in the flume and commanding angular velocity. Thrust and torque will be measured with a six-axis force gage. The actual angular velocity of the motor shaft and the electric current of the motor will be measured using sensors mounted in the thruster. The flow field will be measured with both an acoustic doppler velocimeter and a particle imaging velocimeter (PIV) system. Steady-state experiments will use time-averages of the flow-field to get the statistics. Unsteady experiments will consist of a number of realizations to get an accurate picture of thruster dynamics and the flow. The unsteady experiments will involve: 1.) Step-input tests represented by a sudden jump to a

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constant angular velocity of the propeller, 2.) Tests involving sinusoidal perturbations of the propeller's angular velocity represented by oscillating but non-reversing flow, and 3.) Tests involving large sinusoidal variations of the propeller's angular velocity represented by propeller rotations that alternate between clockwise and counter-clockwise to simulate the control action in waves).

The numerical simulation will be based on vortex-lattice methods developed at MIT to simulate the dynamics of a thruster subjected to a spatially varying and time invariant in-flow current (Keenan, 1989). These methods will be extended to the case of time-varying in-flow current and the angular velocity of the propeller. The steady-state, unsteady step-input tests, and sinusoidal-perturbation tests will be used to verify our numerical models.

Analysis of the experimental flow measurements along with the numerical calculations will be used to develop finite-dimensional models of the thruster hydrodynamics that can be incorporated into vehicle controllers.

## **WORK COMPLETED**

The thruster test facility was built and has been operational since the middle of this year. It is equipped to measure six-degree-of-freedom thruster force and torque data at 8,000 Hertz to 13 bit resolution and 1% accuracy. We have integrated current-mode PWM thruster power amplifiers to give millisecond time-scale current control

The thruster test facility was used to measure unsteady force and flow data. Two fluid flow techniques have been employed: 10MHz acoustic doppler 3-axis flow at 25 samples/sec and 15 Hz particle imaging velocimetry (PIV).

We have written the numerical simulation for performing thrust calculations with time-varying in-flow velocity and propeller angular velocity (Knowles *et al.*, 1996). We are presently comparing the code to the unsteady flow measurements and using it to help interpret the experimental results.

## **RESULTS**

The following are preliminary observations from the experiments some of which have been published in Bachmeyer, Whitcomb, Nakamura, & Grosenbaugh (1997). Thrusters equipped with flow-straightening fixed stator vanes appear to exhibit only modest rotational fluid flow. As anticipated, the stator vanes appear to provide a significant reaction torque, thus decreasing the torque transmitted from the thruster to it's mechanical mounting. Thrusters not equipped with flow-straightening fixed stator vanes appear to exhibit significant rotational fluid flow. The "force overshoot" and "velocity overshoot" exhibited in step torque responses of some thrusters is absent in other thrusters. This may be due to the presence or absence of rotational flow. We have also preformed preliminary volumetric flow mapping of the thruster outflow and observed significant transport delay and dispersion effects.

We are continuing to analyze the data, matching the results with our numerical simulations. We have also developed the beginnings of a finite dimensional control model that incorporates rotational flow into the hydrodynamic model. This new model appears to improve performance, in some cases, over previous control schemes.

## **IMPACT/APPLICATIONS**

The impact of this work will be a control law for AUV thrusters that is based on accurate modeling of the fluid dynamics. The numerical algorithm and experimental work on unsteady dynamics of propellers is new and will add understanding to the thruster dynamics of ships and submarines during radical maneuvers. Finally, the results from designing an observer based on the nonlinear hydrodynamics will yield control schemes that can be used in other applications where nonlinear dynamics dominate.

## **TRANSITIONS**

One of the P.I.'s (Louis Whitcomb) has consulted extensively with William E. Smith at the David Taylor Model Basin concerning our experimental set-up and the experimental instrumentation needs at NSWC and NAVSEA.

The new thruster test stand was used to conduct a comprehensive set of dynamic tests on new marine thrusters that are being developed (with ONR support) by Professor Sam Smith at Florida Atlantic University

## **RELATED PROJECTS**

We presented our experimental results at the semi-annual meeting of the MURI on *Nonlinear Active Control of Dynamical Systems* and will be presenting further results this spring.

## **REFERENCES**

Bachmayer, R., Whitcomb, L., Nakamura, M., and Grosenbaugh, M., 1997. Unsteady six-axis force, torque, and flow dynamical modeling and experiments with marine thrusters, *Proceedings 10th International Symposium on Unmanned Untethered Submersible Technology*, Durham, NH.

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