

A dynamic testbed for supercavitating vehicle control

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Abstract. Supercavitating vehicles are capable of achieving unprecedented speeds due to the presence of a large gas cavity surrounding their bodies. The control design and validation of these vehicles is challenging because planing forces, oscillations, and instability arise when the vehicle pierces the supercavity. In this paper, we propose a methodology to test control algorithms for a supercavitating vehicle subject to planing. With a free-to-rotate scale vehicle in a high-speed water tunnel, we reproduce planing and are capable of assessing active control technologies experimentally. *Sponsored by the Office of Naval Research.*

1. Introduction

Supercavitation is a developed form of cavitation in which a large gas cavity is created behind an object that moves with respect to a fluid. An underwater vehicle surrounded by a gas cavity—supercavity—exhibits a decrease in skin friction drag; therefore, it is capable of achieving higher speed and lower power consumption than conventional vessels. High-speed transportation, ocean exploration, and defense are domains in which supercavitation provides unprecedented benefits. An example is the Ghost vessel [1] that travels above the water surface driven by two underwater supercavitating torpedoes.

We consider a vehicle that consists of a cylindrical body, a sharp disk cavitator located at the vehicle front-end, and two lateral fins at the back-end. At the cavitator edges, the flow separates and the supercavity develops. Steering the vehicle is possible by rotating the cavitator and fins. A scale vehicle with this architecture is shown in Figure 1.

The advantages of supercavitation in terms of speed and power, come along with difficulties in the modeling, control, and experimental validation. In these three domains, the main challenge is the nonlinear interaction between the supercavity and vehicle body. When the vehicle body pierces the supercavity, suddenly a large force hits the vehicle back end. This force, referred to as *planing*, leads to oscillatory motion and sometimes instability. In this paper, we focus on an experimental method to validate control systems for the *longitudinal motion* of a vehicle subject to realistic flow conditions and planing.

Validating control schemes for a supercavitating vehicle in realistic flow conditions is particularly beneficial because the complex vehicle dynamics may not be fully described with a computational model. However, there is a lack of affordable small-scale experimental methods in the open literature to meaningfully validate control strategies for a supercavitating vehicle. In previous work [2], we developed a test method to evaluate control systems for the non-planing dynamics of a supercavitating vehicle. In this article, we propose an approach to validate control



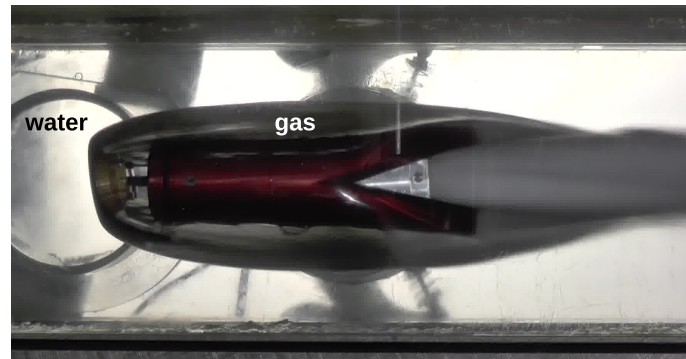


Figure 1: Experimental scale vehicle at the St. Falls Laboratory, University of Minnesota

algorithms subject to the most critical phenomena: planing, oscillations, and instability. This approach could alert engineers of possible pitfalls in the mathematical vehicle model and control algorithms before undersea testing.

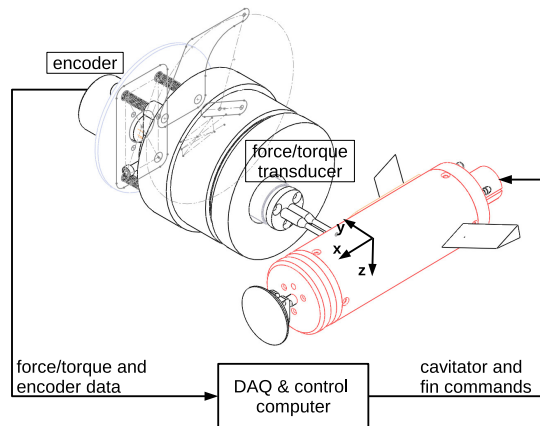
2. Experimental methods

We conceived a methodology to conduct realistic control experiments in the high-speed water tunnel located at the St. Anthony Fall Laboratory. The main idea is that a free-to-rotate scale vehicle naturally achieves planing as the undersea counterpart. Conducting experiments with such a vehicle provides insight into the strengths and drawbacks of control approaches. Although the test method does not reproduce the exact unconstrained motion of a supercavitating vehicle traveling undersea, it captures with exactitude all the hydrodynamic forces. And most importantly, it exhibits the complex nonlinear interaction between the vehicle body and supercavity that originates planing, oscillations, and instability.

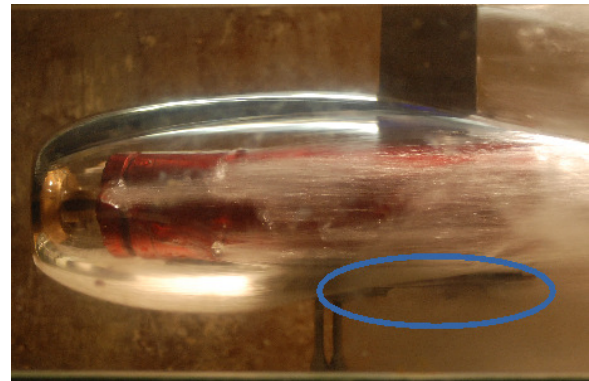
Figure 2a depicts our implementation of the proposed validation platform. A small scale vehicle is employed. It is equipped with a ventilation system that enables the formation of supercavities at speeds above 3 m/s. The test vehicle is a cylinder of 50 mm diameter and 148 mm length with an interchangeable disk cavitator and two interchangeable lateral fins. The fins and cavitator are capable of deflecting ± 20 deg and ± 15 deg respectively. The weight of the vehicle body is 1 Kg. The vehicle rotation, equal to the vehicle attack angle, is measured using a rotary encoder. By translating the vehicle along a slit plate, the vehicle center of rotation and dynamic behavior can be manually adjusted. Between the vehicle and encoder, a force transducer is attached. This transducer rotates together with the vehicle and therefore forces and moments are measured with respect to the vehicle axes.

Real-time measurements of forces, moments, and vehicle attack angle are continuously transmitted to a data acquisition and control computer (DAQC²). The force and torque measurements are transmitted to the DAQC² via an Ethernet interface in a local area network. The encoder data are read by an NI PCI-6902 data acquisition card. The same card is used to generate Pulse Width Modulated (PWM) signals that command the positions of the actuators attached to the cavitator and fins. By commanding the cavitator and fins, the algorithms running onto the DAQC² control the vehicle motion.

A high-speed camera is used to characterize the supercavity dynamics and analyze the experiments. Synchronization between the DAQC² and video streams is achieved using an Light Emitter Diode (LED) connected to the NI PCI-6902 card. When the control experiment starts, the LED is turned on. The software running on the DAQC² is implemented under MATLAB/Simulink and Real-Time-Windows-Target (RTWT) with a sampling frequency of 100 Hz. Key features of the proposed platform include:



(a) Schematic



(b) Induced lateral planing

Figure 2: Experimental Facility

- enables the modeling of hydrodynamic forces and supercavity dynamics
- provides an affordable solution to validate control schemes for supercavitating vehicles after design and before undersea testing
- recreates realistic flow conditions, oscillations, and instability

The main limitation of the platform is that the supercavity is pierced by the rotational shafts, leading to lateral planing. Figure 2b illustrates the induced planing regions. Lateral planing slightly damps the vehicle rotations and partially attenuate the effect of planing forces. Yet, the system exhibits oscillations and instability due to planing, as desired to assess controllers.

3. Vehicle dynamics and controls

The dynamics of both the unconstrained vehicle traveling undersea and the experimental vehicle in the tunnel share the same structure. Both dynamics are driven by the forces at the cavitator, fins, and planing regions, as well as the gravity. Figure 3 depicts a general scheme of the vehicle dynamics G composed of the supercavity and body dynamics G_s and G_b respectively. G is described by a nonlinear differential equation. According to the design method, the controller K may be described by a static gain or a linear/nonlinear differential equation. Its main objective is to drive the vehicle to a desired state by using the cavitator and fin commands u . For the test vehicle in the tunnel, the goal of K is to track attack angle commands. In this case the measurement y is equal to the vehicle attack angle α .

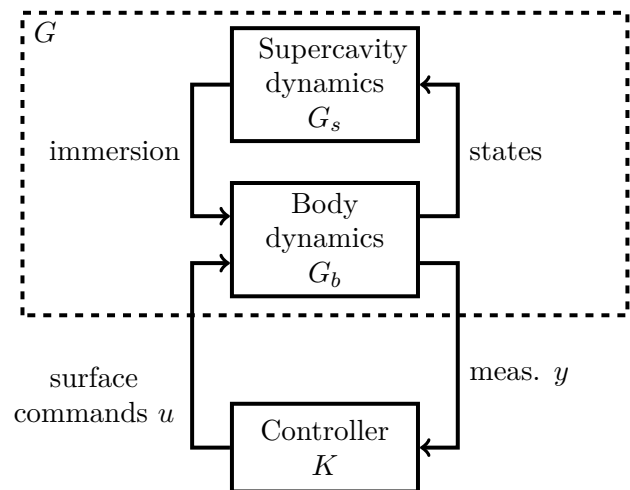


Figure 3: Vehicle and controller dynamics

4. Experiments

The main objective of the experiments we conducted was to assess diverse control schemes that we designed. An overall procedure to evaluate a controller consists of: (i) creating a mathematical model G of the vehicle and supercavity motion, (ii) synthesizing a controller K , (iii) designing the attack angle commands to assess the controller, and (iv) conducting the experiment in the

water tunnel. We carried out two experiments to evaluate how the control systems perform under realistic flow conditions. A controller K_1 was designed to track reference commands r so that $r - \alpha$ is minimized at all times. This controller was designed with a model that assumes no planing. A controller K_2 was designed to track commands r while guaranteeing performance in the face of planing. Both controllers were evaluated using step-up and step-down commands from -2 to 4 deg. When the vehicle rotates towards 4 deg, planing emerged.

5. Results

The results of the aforementioned experiment are presented in Figure 4. The top plot shows the responses of the vehicle attack angle to reference commands with controllers K_1 and K_2 . The controller K_1 exhibits oscillations when the vehicle is subject to planing. These oscillations are minimized by K_2 , designed to operate under planing conditions. In the middle plot, the cavitator deflections are presented. Interestingly, K_2 demands larger cavitator deflections than K_1 , to move the supercavity and thereby minimize planing immersion. Since K_2 mostly uses the cavitator for control, it requires smaller fin deflections than K_1 . The bottom plot illustrates the fin deflections. Our results suggest that including planing within the controller scheme significantly improves its performance.

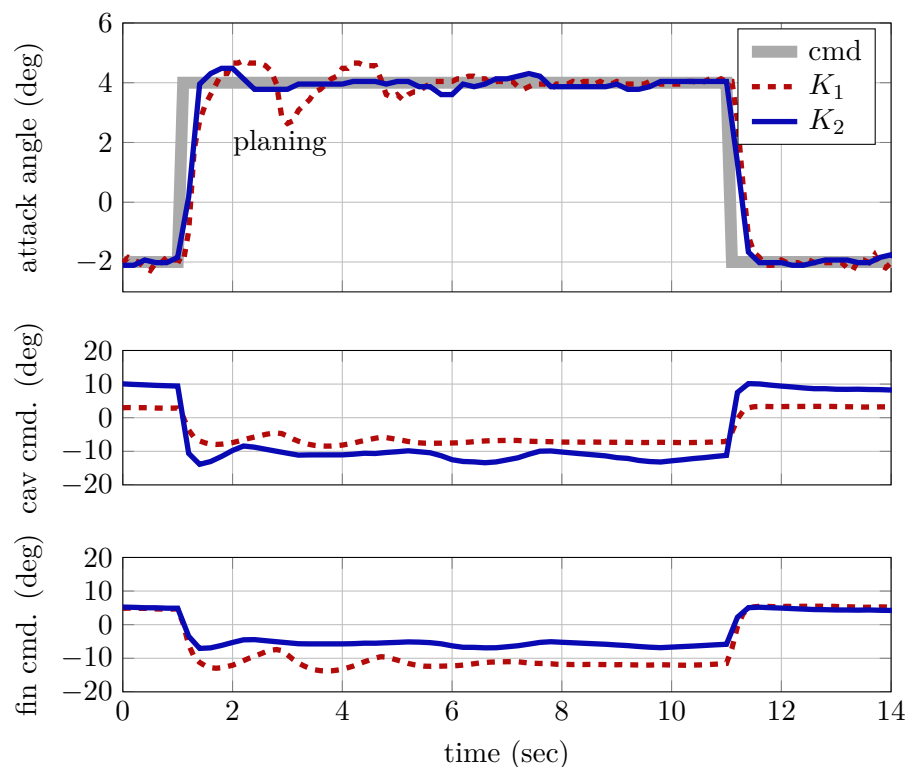


Figure 4: Experimental data with controllers K_1 and K_2

6. Summary and conclusions

We have shown that a free-to-rotate supercavitating vehicle in a high-speed water tunnel can be employed to assess control technologies for a supercavitating vehicle. This method is an affordable validation approach for research and development.

References

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- [2] Escobar D, Balas G and Arndt R E 2014 *Oceanic Engineering, IEEE Journal of* **PP** 1–12 ISSN 0364-9059