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A Dynamic Test Platform for Evaluating Control Algorithms for a Supercavitating Vehicle

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ABSTRACT

The use of supercavitation to enable marine vehicles to travel at extraordinary speeds is a topic of considerable interest. The control of these vehicles poses new challenges not faced with fully wetted vehicles due to a complex interaction between the vehicle and the cavity that it rides in. Some of the existing models make assumptions that may not be valid for a maneuverable vehicle. Furthermore, since there are various models being suggested for planing forces as well as different ways of obtaining fin and cavitator forces, there is a lack of unity among the equations used to calculate the hydrodynamic forces imparted on such a vehicle. Experimental test platforms have been developed at St. Anthony Falls Laboratory to enable testing and validation of control algorithms and hydrodynamic models. Previous efforts have revealed the destabilization of marginal supercavities by control surfaces, especially when a cavity is being maintained with ventilation [1]. Our latest water tunnel test platform is a body of revolution with an actuated cavitator on the model forebody, actuated fins that protrude through the cavity surface, and variable pitch of the model body, all supported by a six-axis force balance. In this paper we will present a brief description of the forces present in our mathematical model of a supercavitating vehicle, and then present the new experimental test platform that will be used to validate, and expand on this model.

INTRODUCTION

The phenomenon of supercavitation permits objects to move through water at high speeds because of an order of magnitude reduction in skin-friction drag. Applications of supercavitation include underwater munitions such as torpedoes and projectiles, propellers and pumps, and hydrofoils. In order to capitalize on the phenomenon, operation must either be at high speed or artifical ventilation of the cavity must be resorted to.

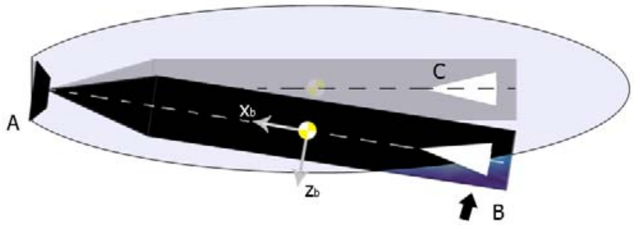

Figure 1 Diagram of a nominal supercavitating vehicle in longitudinal plane. A) Disk cavitator B) Planing force on afterbody C) Wedge shaped fins.

This paper focuses on the operation of a nominal high-speed supercavitating vehicle (HSSV). Only small regions at the nose (cavitator) and on the afterbody are in contact with water. For this nominal HSSV only three primary hydrodynamic forces are present, as shown in Figure 1: cavitator forces, after body planing forces, and fin forces. Any attempt at vehicle stabilization and control must be accomplished using a combination of these three. The absence of lift on the body (unlike a fully wetted vehicle) requires that the body must either be in a planing mode or the control surfaces must provide the necessary lift. Cavity shape is very important when computing the forces acting on the supercavitating vehicle and consideration has to be given to the nonlinear interaction of the control surfaces and the body with the cavity wall. Furthermore, the cavity-vehicle interaction exhibits strong memory effects (cavity shape is a function of the history of the vehicle motion) that must be included in the modeling.

DYNAMIC MODELING ISSUES

Cavitator

Our discussion is limited to circular disk shaped cavitators. Experimental testing of cavitators at angles of attack for a range of cavitation numbers has been presented in Kiceniuk [2]. The available information seems sufficient for modeling and control design purposes. One of Kiceniuk's findings is that "tangential friction forces are negligible as compared to the normal pressure forces." Employing the notation in Figure 2, the experimentally determined expressions for the normal force on the cavitator are presented in [3]:

Equation 1 $\boldsymbol{c_x = 0.82(1+\sigma)}$

Gives the drag coefficient (c_x) of a disk at nonzero cavitation numbers (σ).

Equation 2 $\boldsymbol{W_o = c_x \frac{1}{2} \rho V^2 S_n}$

Gives the drag on the disk (W_o) where ρ, V, and S_n are water density, free-stream velocity, and the reference area respectively. For a disk of radius R_n, $S_n=\pi R_n^2$.

Equation 3 $\boldsymbol{\alpha_{cav} = \alpha_{body} - \delta_{cav} - \tan^{-1}\left(\frac{qL_{cav}}{V}\right)}$

Gives the local angle of attack (α_{cav}) for the cavitator, which is a function of the vehicle angle of attack (α_{body}), cavitator deflection (δ_{cav}), and the pitch rate (q) induced angle of attack.

Equation 4 $\boldsymbol{W_n = W_o \cos \alpha_{cav}}$

Gives the pressure force acting normally on the disk with an angle of attack (α_{cav}). Experiments show that Equation 4 is valid for $\alpha_{cav} < 45°$.

Next we will translate the normal force acting on the cavitator to the vehicle body axis.

Equation 5 $\boldsymbol{F_{cav} = \begin{bmatrix} -W_n \cos \delta_{cav} \\ 0 \\ -W_n \sin \delta_{cav} \end{bmatrix}}$

Gives the forces on the cavitator in the body frame (x_b, y_b, z_b).

Equation 6 $\boldsymbol{M_y = L_{cav} W_n \sin \delta_{cav}}$

Gives the pitching moment induced by the cavitator forces.

Note in Equation 6 that if the cavitator is not deflected ($\delta_{cav}=0$) then regardless of the vehicle angle of attack, there will be no moment imparted to the vehicle. Furthermore as reported in [2], the moment coefficient on the disk cavitator (CM) is zero, to within the estimated error of ± 0.05. This, and other uncertain hydrodynamic coefficients may be included in our control system design as parametric uncertainty.

Note that this conclusion holds for disk cavitators. Other cavitator shapes, such as the 15° half angle cone, would impart moments to the vehicle even when not deflected so long as the cavitator has an angle of attack [2].

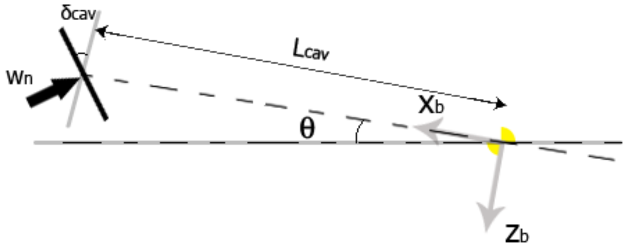

Figure 2 Cavitator shown isolated from supercavitating vehicle. Vehicle pitch (θ) is positive clockwise, by the right hand rule. Cavitator deflection (δ_{cav}) is positive counterclockwise, so positive deflection generates lift. The dominant normal pressure force on the cavitator is W_n and the distance between the vehicle's center of mass and cavitator pivot is L_{cav}.

Planing Forces

Various models of planing forces are available. However, the controls community has yet to settle on a planing model that is deemed capable of adequately capturing the dynamics of planing. This is a topic that will be pursued in the future.

Fin Forces

Fins help to stabilize a supercavitating vehicle. The varying wetted area of the fins and the fact that they will be cavitating/supercavitating make the modeling of fin forces non-trivial. Until now, most control simulations have used a fin force/moment lookup table for wedge shaped fins generated using numerical methods by Anteon Corporation and presented in [4]. An extensive experimental investigation of wedge shaped cavitating hydrofoils are presented in [5]. It is our plan to incorporate the experimental data into our simulation and then validate the results using our experimental test bed.

Modeling

Using the available equations, multiple simulation models describing supercavitating vehicles have been developed, ranging from one degree of freedom longitudinal axis models to full six degree of freedom models. These simulation models have yielded a better understanding of the dynamics of supercavitating vehicles, which is important when designing control strategies. Furthermore, these models have identified several critical parameters that hydrodynamics research must address. For instance there is a need for an accurate description of the cavity shape during maneuvers and it has been found that the planing description used in the model has an immense impact on the vehicle dynamics. An accurate planing model is essential for further advances.

Our experiments at the St. Anthony Falls Laboratory (SAFL) water tunnel have identified several phenomena that need to be investigated further and incorporated into the control model. Specifically the interaction between control surface actuation and cavity dynamics is an important issue. Control surfaces are typically supercavitating, and it has been found that fin supercavities experience hysteresis with respect to fin angle of attack. These fin supercavities deflect the main body supercavities, and increase ventilation demand. Stabilty of the main cavity can become an issue [1].

As part of an ongoing research program to model and develop robust control laws for the full operating envelope, we have embarked on an interactive program of control simulations and water tunnel experiments with the objective of:

- Further investigation of the effects of supercavitating fins
- Test candidate fin and cavitator shapes
- Investigate supercavity stability when control surfaces are actuated
- Investigate supercavity hysteresis
- Validate look-up tables for forces and moments generated by control surfaces
- Test the effectiveness of different control surface combinations
- Investigate planing forces
- Implement simplified versions of the control strategies developed and “close the loop” .

EXPERIMENTAL SET UP

In order to meet these objectives a new Control Surface-Cavity Interaction Simulator (Mo II CoSCIS) was developed. The Mo II CoSCIS simulates a generic supercavitating vehicle and is shown in Figure 3 and Figure 4. It consists of a smooth cylindrical body, with an actuated cavitator at the front and two actuated horizontal fins at the back. The cavitator and fins can be taken off and replaced, to test different candidate shapes, while the fins can be kept off when looking at the cavitator only case. Both the fins and the cavitator are actuated in the longitudinal plane, independently of each other. Behind the cavitator at the front of the cylindrical body are a series of ventilation ports, evenly distributed along the circumference of the body, these are shielded by a metal collar that directs the ventilation flow downstream. By mounting the vehicle model onto the shaft of a six-degree of freedom force and moment sensor, we can measure the total lift, drag and pitch moment that the model experiences.

This design enables us to generate a ventilated axisymmetric supercavity around the actuated cavitator at the front, and have two actuated fins piercing through the supercavity at the back. The ability to vary the pitch of the model enables us to investigate planing by having the supercavity hit the cylindrical body of the vehicle model.

The model is mounted in the SAFL 19 x 19 cm high-speed water tunnel and is interfaced with our control simulation package as shown schematically in Figure 5. The water tunnel can be fitted with an upstream gust simulator to provide an unsteady flow environment for control studies.

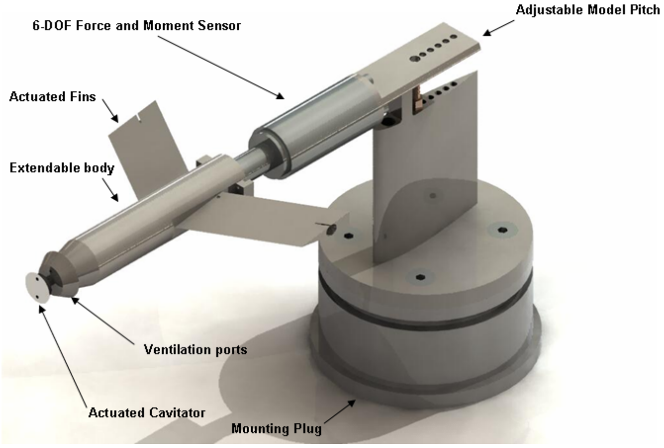

Figure 3 Control Surface-Cavity Interaction Simulator (Mo II CoSCIS).

RESULTS

Using the experimental platform described above, we intend to begin validating our simulation model by comparing the dynamic equations to experimental results. Preliminary testing has begun in the SAFL water tunnel, as shown in Figure 6.

ACKNOWLEDGMENTS

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NOMENCLATURE

CoSCIS	Control Surface-Cavity Interaction Simulator
c_x	Disk drag coefficient
F_{cav}	Forces on cavitator in the body frame
HSSV	High-speed supercavitating vehicle
L_{cav}	Distance from center of mass to cavitator
M_y	Cavitator induced pitching moment
q	Vehicle pitch rate
R_n	Radius of disk cavitator
S_n	Cavitator reference area
V	Free-stream velocity
W_n	Normal force on disk cavitator
W_o	Drag on the disk cavitator
x_b, y_b, z_b	Body-fixed coordinate frame
α_{body}	Vehicle angle of attack
α_{cav}	Cavitator angle of attack
δ_{cav}	Cavitator deflection
θ	Vehicle pitch angle
ρ	Water density
σ	Cavitation number

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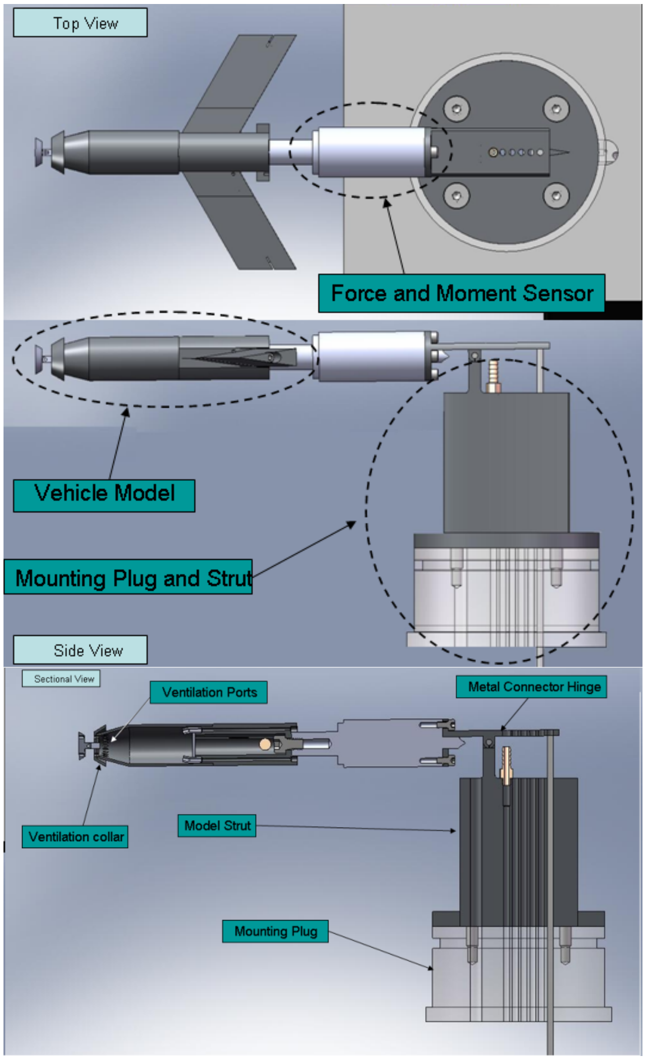

Figure 4 Sectional view of Mo II CoSCIS.

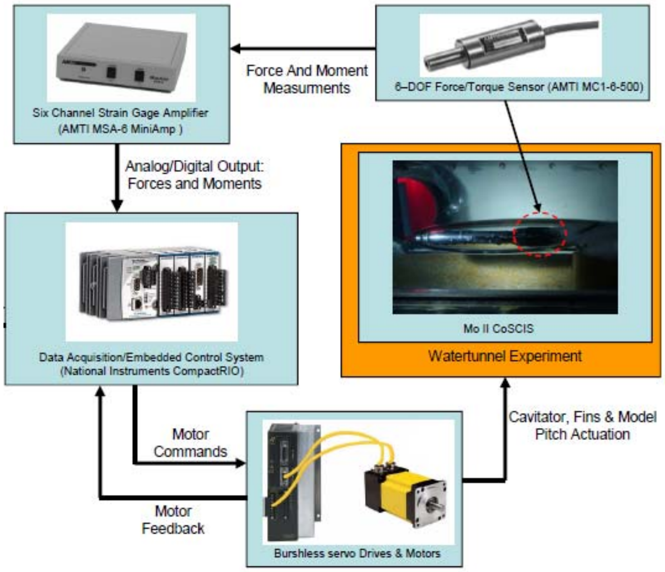

Figure 5 Integration of simulator into the water tunnel experiments.

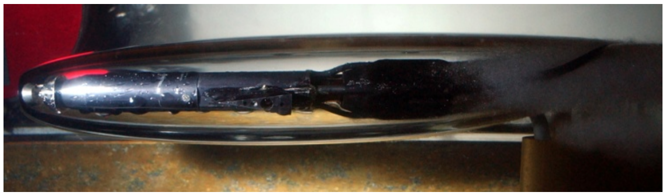

Figure 6 Mo II CoSCIS operating in the SAFL water tunnel.