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Robust control of a small-scale supercavitating vehicle: From modeling to testing☆

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ABSTRACT

By traveling inside a gas cavity, a supercavitating vehicle can reduce hydrodynamic drag, increase speed, and minimize power consumption. The main challenge for controlling a supercavitating vehicle is a nonlinear force that arises when the vehicle back-end pierces the cavity. This force, referred to as planing, leads to oscillatory motion and instability. In an effort to develop robust control technologies for supercavitating vehicles, we developed and tested a control methodology for a small-scale system capable of freely rotating about its pitch axis in a high-speed water tunnel. We constructed a low-order nonlinear model of the longitudinal vehicle motion that is based on experimental observations and physical principles. By using this model, we developed a controller design method that delivers a proof of performance in the face of nonlinear and uncertain planing forces. Experiments with the vehicle prototype in the water tunnel suggest that the proposed control technique ensured higher performance when the uncertain planing dynamics are considered in the control synthesis.

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, referred to as supercavity, exhibits a decrease in contact area with the fluid, a reduction of skin friction drag, and ultimately an increase in speed (J. M. S. Inc,). The attainable speeds and power efficiency of supercavitating vehicles open new possibilities for high-speed transportation, ocean exploration, and defense. However, traveling inside a supercavity brings new challenges to the development of robust control systems for these vehicles. When the vehicle is fully enveloped by the supercavity only the nose of the vehicle (cavitator) and fins are wetted. When the vehicle back-end pierces the supercavity and immerses into the fluid, a large slapping force is suddenly created. This force, referred to as *planing*, can cause oscillatory motion and instability. Developing control strategies that guarantee stability and performance in the presence of planing is a challenge because low-order vehicle models typically used for control design do not accurately capture the complex planing physics.

Several strategies have been proposed for the control of the benchmark vehicle model presented in (Dzielski and Kurdila, 2003). The investigations in (Mao and Wang, Dzielski and Kurdila, 2003; Balas et al., 2006; Vanek et al., 2007; Mao and Wang) use nonlinear inversion, sliding mode control, and linear parameter varying (LPV) techniques to control the dynamics of a supercavitating vehicle traveling at a fixed axial speed. These strategies rely on idealized low-order models of the supercavity to estimate planing forces and schedule the controllers. The control strategy presented in (Lin et al., 2010) use sector bounds to characterize the planing force and validate the absolute stability of the controller and vehicle mathematical model presented in (Dzielski and Kurdila, 2003). To validate proposed control systems considering the inaccuracy in the planing models, numerical simulations have been used (Mao and Wang, Balas et al., 2006; Mao and Wang). A limitation of using numerical simulations is that they do not provide a proof of stability and performance in all possible scenarios. In an effort to address this limitation, we developed and tested a robust control framework for a small-scale supercavitating vehicle capable of rotating about its pitch axis in a high-speed water tunnel. In particular, we derived a low-order model of the vehicle dynamics that includes modeling uncertainty, developed tools for the synthesis of robust controllers based on the uncertainty vehicle model, and validated the controllers in the high-speed water tunnel. The proposed strategy is suitable for reference tracking, does not

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require real-time measurements of planing, and could be extended to design control systems for large-scale vehicles.

This paper is organized as follows. In Section 2, we present the vector notation and coordinate transformations used throughout the paper as well as a brief introduction to supercavitation. In Section 3, we describe the small scale vehicle and experimental facilities used for mathematical modeling and control testing. The mathematical model of the small scale vehicle is developed in Section 4. In Section 5, we describe the control synthesis tools developed for the experimental vehicle. Results of testing the proposed control laws with the experimental vehicle prototype in a high-speed water tunnel are presented in Section 6. In Section 7 we present the limitations of this study. Conclusions and future directions are presented in Section 8.

2. Preliminaries

2.1. Vector notation and transformations

The vector notation described as follows is used throughout this paper to characterize the vehicle and supercavity motion. A vector representing the position of a point or a coordinate frame $\{B\}$ with respect to a coordinate frame $\{A\}$ is denoted by ${}^{\mathrm{A}}\mathrm{P}_{\mathrm{B}} = \begin{bmatrix} A_{xB} \\ A_{zB} \end{bmatrix}$, with angles positive from ${}^{A}z_{B}$ to ${}^{A}x_{B}$.

The position of point f with respect to frame $\{A\}$, given its position relative to frame $\{B\}$ and the relative position between frames ${}^{A}P_{B}$ is given by the following homogeneous transformation (Craig, 2005)

$$\begin{bmatrix} {}^{\mathrm{A}}\mathrm{p}_{\mathrm{f}} \\ 1 \end{bmatrix} = \begin{bmatrix} {}^{A}_{B}R & {}^{\mathrm{A}}\mathrm{p}_{\mathrm{B}} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} {}^{\mathrm{B}}\mathrm{p}_{\mathrm{f}} \\ 1 \end{bmatrix} = {}^{A}_{B}T(\gamma_{BA}, {}^{\mathrm{A}}\mathrm{P}_{\mathrm{B}})\, {}^{\mathrm{B}}\widehat{\mathrm{p}}_{\mathrm{f}}$$

where ${}^{A}_{B}R$ is a rotation transformation based on angle γ_{BA} measured between $\{B\}$ and $\{A\}$.

The derivative of a position vector ${}^{\mathrm{B}}\mathrm{p}_{\mathrm{f}}$ with respect to time and relative to $\{B\}$ is given by ${}^{\mathrm{B}}\mathrm{V}_{\mathrm{f/B}} = \frac{d\,{}^{\mathrm{B}}\mathrm{p}_{\mathrm{f}}(t)}{dt}$. The velocity of f relative to $\{B\}$, but expressed with respect to $\{A\}$ is ${}^{\mathrm{A}}\mathrm{V}_{\mathrm{f/B}} = {}^{A}_{B}R\,{}^{\mathrm{B}}\mathrm{V}_{\mathrm{f/B}}$. When the velocity of f relative to $\{B\}$ is expressed with respect to the inertial frame $\{E\}$, we use $\mathbf{V}_{\mathbf{f/B}} = {}^{\mathrm{E}}\mathrm{V}_{\mathrm{f/B}}$. The velocity of f relative to $\{E\}$ and expressed with respect to $\{E\}$ is denoted by ${}^{\mathrm{E}}\mathrm{V}_{\mathrm{B/E}} = \mathbf{V}_{\mathbf{f}}$. Additionally, the velocity of a frame $\{B\}$ relative to $\{E\}$ but expressed with respect to $\{B\}$ is ${}^{\mathrm{B}}\mathrm{V}_{\mathrm{B}} = {}^{\mathrm{B}}\mathrm{V}_{\mathrm{B/E}} = {}^{B}_{E}R\,{}^{\mathrm{E}}\mathrm{V}_{\mathrm{B}}$.

2.2. Supercavitation

The cavitation number, defined as $\sigma \overset{\mathrm{def}}{=} \frac{2(p_\infty - p_c)}{\rho |\mathrm{V}_{\mathrm{C/f}}|^2}$ is a parameter that describes supercavitation. p_∞ is the pressure outside the supercavity, p_c is the pressure inside the supercavity, ρ is the fluid density, and $|\mathbf{V}_{\mathbf{C/f}}|$ is the relative speed between the cavitator center of pressure (c.p) and the fluid. By decreasing σ, the likelihood of developing supercavitation increases. The cavitation number can be lowered and supercavitation achieved by either increasing $|\mathbf{V}_{\mathbf{C/f}}|$ or by decreasing the difference $p_\infty - p_c$. In open waters, supercavitation is naturally achieved when $\sigma < 0.1$ approximately. When supercavitation is naturally achieved, p_c is the vapor pressure. Injecting air behind the cavitator increases p_c and allows for the formation of ventilated supercavities at low speeds. *Ventilated supercavitation* can be used to form supercavities until reaching natural supercavitation at higher speeds and for experimentation in water tunnels.

The supercavity dimension is a function of σ, blockage, and the gravitational acceleration g. As σ decreases, the supercavity length and diameter increase. When supercavitation experiments are conducted in a high-speed water tunnel, the supercavity can exhibit a decrease in its diameter and an increase in its length due to the presence of the tunnel walls (blockage). A supercavity can also exhibit asymmetric shapes due to gravity and in water tunnels due to its relative position with the tunnel walls. The effect of gravity on the supercavity asymmetry is negligible when $\frac{|\mathrm{V}_{\mathrm{C/f}}|}{gD_c} \to \infty$ with D_c being the cavitator diameter.

3. Experimental methods

3.1. Facilities

Experiments presented in this paper were carried out in the high-speed water tunnel located at the University of Minnesota St. Anthony Falls Laboratory (SAFL). This tunnel is a recirculating, closed circuit facility capable of regulating absolute pressures and achieving velocities up to 20 m/s. Its test section is 0.19 m (width) by 0.19 m (height) by 1 m (long) (Kawakami and Arndt, 2011).

The supercavitating scale vehicle shown in Fig. 1 was used for both vehicle modeling and controller validation. This vehicle was equipped with a ventilation system that enabled the formation of supercavities at speeds above 3 m/s. The test vehicle consisted of a cylinder of 50 mm diameter and 148 mm length with an interchangeable disk cavitator and two interchangeable lateral fins. Two servo actuators located inside the vehicle deflected the cavitator and fins. The maximum deflections of the fins and cavitator were ± 20 deg and ± 15 deg, respectively. The vehicle's weight was 1 Kg. The water speed upstream from the cavitator was calibrated via a Laser Doppler Velocimetry system. Based on this calibration we adjusted the water speed for modeling and control experiments. The water velocity vector upstream from the cavitator is perpenticular to the gravity vector.

An oscillating foil (gust generator) was used to perturb the flow and study the supercavity dynamics. By perturbing the flow, we varied the cavitator attack angle and thereby displaced the supercavity upwards and downwards. When the supercavity displacements due to gust oscillations were large, we were able to generate planing and characterize planing forces applied at the vehicle back-end.

3.2. Modeling

We constrained the vehicle motion to characterize the supercavity kinematics as well as the forces at the cavitator, fins, and planing regions. The back-end of the scale vehicle was attached to a force and torque transducer that was in turn attached to the tunnel through a strut. This force transducer was used to quantify how forces changed due to variations in planing immersion as well as cavitator and fin deflections.

A high-speed camera recorded videos of the supercavity kinematics and the interaction between the vehicle body and supercavity. To accurately capture the supercavity dynamics, we recorded videos of the water tunnel experiments at 1000 frames per second. The videos were synchronized with a data acquisition and control computer via a light emitter diode (LED) that was turned on when the experiments started. By perturbing the supercavity via the gust generator oscillations, we

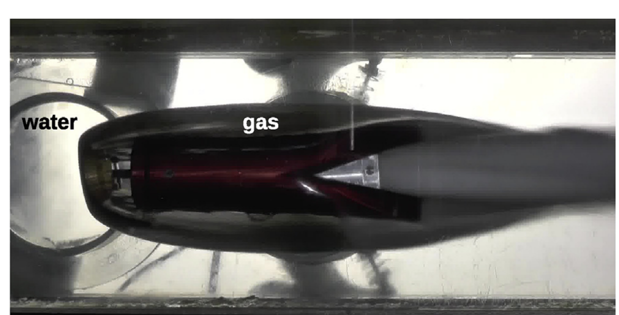

Fig. 1. Experimental small-scale vehicle at the St. Falls Laboratory, University of Minnesota.