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Modeling and simulations of supercavitating vehicle with planing force in the longitudinal plane

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ABSTRACT

Pitching motion is one of the most important characteristics in the longitudinal plane for the maneuvering supercavitating vehicle. In this case, supercavity is unsteady to dramatically change hydrodynamic distribution of its vehicle because of some factors such as changes of ambient pressure and control surfaces, gravity, inertial force, and so on. More importantly, planing force is usually produced to provide restoring force and moment for motion stability. The maneuvering supercavity model is applied to model supercavitating vehicle with planing force in the longitudinal plane. The corresponding numerical algorithm is developed to simulate uncontrolled vehicle making a diving motion in the longitudinal plane and calculate planing force based on the model. The algorithm includes two intercoupling sub-algorithms: the self-developed cavitation number embedded coefficient correction algorithm for unsteady supercavity and Runge–Kutta algorithm for vehicle's trajectory. The model and numerical algorithm are validated to some extent by comparing numerical results with ones of the empirical supercavity model applied widely.
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1. Introduction

Supercavity is applied to achieve a great drag reduction by enveloping its vehicle almost fully as an extreme state of cavitation. For this reason, researchers have done quite a lot of work and gotten tremendous results in this field. With the development of research, the controllability and maneuverability of supercavitating flows and their vehicles are increasingly becoming the focus of research. In this case, supercavity is unsteady to influence hydrodynamic distribution of its vehicle dramatically under the influences of ambient flow field and vehicle's control surface, so it is very difficult to acquire vehicle's dynamics properties for realizing its controllability and maneuverability. Also, in order to keep motion stability, planing force is produced to provide restoring force and moment. Hence, it is the basis of realizing the controllability and maneuverability to model a maneuvering supercavity and its vehicle considering planing force.

Savchenko [1,2] has presented four possible stable motion schemes of supercavitating vehicles and some problems on modeling of supercavitating flows in experiment. Furthermore, some research results and remaining questions have been discussed by Serebryakov et al. [3] on supercavitation motion at sub-, trans-, supersonic Mach numbers. In the modeling, some supercavity models [4–8] have been established based on Logvinovich's principle. Yu et al. [9] and Zou et al. [10] have modeled the maneuvering supercavity with effects of gravity, angle of attack (AOA) and inertial force in a curvilinear motion

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in the vertical and horizontal planes, respectively. Further, the supercavity model has been developed by Zou and Liu [11] to simulate supercavitating vehicle with tail-slaps, and been validated by experiment. Lindau et al. [12] have developed a numerical simulation model of supercavitating vehicle based on a preconditioned homogenous multiphase unsteady Reynolds Averaged Navier–Stokes flows coupling with a six-degree-freedom rigid body without control surfaces, and simulated it with a forward motion. A linear analysis has been made by Grant and Kirschner [13] to predict wave pattern for a projectile at high speed through a bubbly flows. In order to further study dynamics characteristics of supercavitating vehicle with planing force, Kubenko and Gavrilenko [14] have focused on the early stage of impact of a solid cylindrical body on a cylindrical cavity surface for zero and non-zero gap between cavity and body surfaces during supercavitation motion in a compressible fluid. Also, some empirical cavity models [15,16] are usually used to analyze dynamics and stabilities of supercavitating vehicle. Numerical simulations based on N–S equations are very practical and widely applied to research supercavitating flows. Lee and Byun [17] have studied incompressible turbulent cavitating flow around axisymmetric body using SIMPLE algorithm based on Kunz cavitation model and $k-\varepsilon$ turbulent model with wall function, while Hu et al. [18] have modified the dispersion-controlled dissipative scheme to simulate supercavitating flows using a robust scheme initially for capturing shock wave in gas dynamics based on one-fluid model. The three-component cavitation model [19] is proposed to simulate natural and ventilated cavitating flow around an underwater vehicle. Influences of flexible free surface and rigid bottom wall on supercavity have been analyzed by Chen et al. [20] in shallow water using VOF (Volume of Fluid) method. In order to study hydrodynamic forces, Yu et al. [21] have researched lift distribution on the afterbody of ventilated supercavitating vehicle in water tunnel. Also, pitching motions of supercavitating vehicle are simulated by Pan et al. [22] and Yu et al. [23] in the longitudinal plane. Experimentally, in order to develop a better computational model, Li et al. [24] have observed supercavitation around a hydrofoil using a high-speed video camera and PIV technique. Some experiments were carried out by Kawakami and Arndt [25] to determine flow mechanism of supercavitating vehicle in supercavity shape, closure, and ventilation requirements versus Froude number. Cameron et al. [26] have studied supercavity shape and hydrodynamic forces of supercavitating projectile during the free-flying flight in experiment, and verified research results by theoretical models. Various types of available facilities have been discussed by Fedorenko et al. [27] to investigate inertial motion of high-speed supercavitating bodies.

Although research on modeling and simulation of supercavity and its vehicle have achieved great progress, supercavitating vehicle still needs a further research in a maneuverable motion. Besides, steady and empirical supercavity models are usually applied to dynamics and control of high-speed motion body so far, and have great limitations in the modeling of maneuvering vehicle. In this paper, the maneuvering supercavity model with gravity, AOA and inertial force effects is applied to model supercavitating vehicle with planing force and control surfaces in the longitudinal plane. Based on this model, the numerical algorithm is developed to simulate pitching motions of uncontrolled vehicle in the longitudinal plane and calculate planing force. The simulation provides two coupling algorithms allowing the determination of the vehicle trajectory as well as the unsteady supercavity and hydrodynamic distribution. The first is based on the classic Runge–Kutta algorithm and the second on the self-developed cavitation number embedded coefficient correction algorithm. Finally, the supercavity model and numerical algorithm are verified by comparing numerical results with ones from the empirical one [28–30] applied widely in the field of the dynamics and control of supercavitating vehicle. This study contributes to model and simulate controllable vehicle in the high-speed motion.

2. Mathematical model of supercavitating vehicle

For supercavitating vehicle in a maneuvering motion, supercavity definitely has unsteady characteristics determining vehicle's dynamics and stability under the influences of ambient flows and control surfaces. Hence, it is imperative to develop an effective maneuvering supercavity model to build dynamics model of its vehicle.

2.1. Maneuvering supercavity model

Considering effects of gravity, AOA and inertial force, the supercavity model is established in the longitudinal plane using the bubble dynamics method based on Logvinovich's principle. The model is described by basic and effects equations. The point to emphasize here is that all equations of the supercavity model are formulated in our previous studies [9,10,31] except expansion equation of supercavity section.

2.1.1. Basic equations

Basic equations consist of the expansion equation (1) and mass balance equation (3), and constitute a closed set of equations to describe unsteady axisymmetric ventilated supercavity if ventilation and gas-leakage rates are known. According to Logvinovich's principle, supercavity section expands independently on each continuous plane perpendicular to cavitator's trajectory in an inertial coordinate system. Serebryakov [6] and Vasin [8] have derived the section equation with the framework of potential flow theory below, respectively:

$$\frac{\partial^2 S_c(\tau,t)}{\partial t^2} = -\frac{k\Delta p(\tau,t)}{\rho_w}, \tag{1}$$

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