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Three-dimensional ventilated supercavity on a maneuvering trajectory

Wang Zou *, Hua Liu, Lei-Ping Xue

MOE Key Laboratory of Hydrodynamics, Department of Engineering Mechanics, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

One major practical application of supercavitation is to develop a maneuvering supercavitating vehicle. Research into three-dimensional maneuvering supercavities is essential to achieving this goal. The effect of inertial force on a cavity, triggered by the pressure difference between the inner and outer surfaces of the cavity, is modeled on the maneuvering trajectory, and increases as the trajectory radius decreases. Taking this effect into account as well as other factors (lateral force on the cavitator, gravity and ocean waves), a maneuvering supercavity model is established in the three-dimensional space. Based on this model, a numerical algorithm is developed to simulate the maneuvering motion of a supercavity prescribed by the deflection angle of the cavitator and speed disturbance, and its motion characteristics are analyzed. The results indicate that the supercavity deforms with the offset of its centerline on the maneuvering trajectory. The pressure gradient in the vertical plane is an essential factor in this deformation, with centerline deviation from the movement path dominated by gravity, lateral force on the cavitator and inertial force. Lateral and inertial forces play a much greater role in the deviation than gravity does. Pressure inside the cavity oscillates with its varying mean throughout the maneuvering motion, and even once the cavity returns to a cruising state, internal pressure still pulsates with a uniform amplitude as an intrinsic attribute of an unsteady ventilated cavity.

1. Introduction

Supercavitation can greatly reduce drag on a vehicle. The possibilities for broad application and the complicated flow mechanism involved have attracted much scientific attention worldwide since the discovery that it is possible to form supercavities by ventilation. There has been extensive research in this field, and some progress has been made; as understanding has increased, research has focused on controlling and maneuvering a supercavitating vehicle. However, the supercavity usually deforms violently, and even sheds to influence the hydrodynamic distribution of its vehicle due to changes in ventilation, ambient pressure, control surfaces and thrust during maneuvering. In this case, it is difficult to predict the vehicle's dynamic properties for manipulation. It is thus imperative to establish a three-dimensional maneuvering supercavity model that is relatively simple in form, and to develop a numerical algorithm to calculate shape characteristics based on the model that can be used in the vehicle's control system without large time costs.

Through many experiments, Logvinovich's principle (Logvinovich, 1969) has been proposed as a theoretical basis for modeling cavity. Compared with multiphase flow models, the cavity dynamics model, in which the cavity section equation is obtained based on Logvinovich's principle, has immanent advantages in flexible modeling and small computational cost, and is an important first step in understanding the dynamics and control of a supercavitating vehicle in complicated flow states (Kirschner and Arzoumanian, 2008). Using an asymptotic approach in the frame of the slender body theory, Serebryakov (1974, 1976) first derived a cavity section equation with accurate initial conditions to describe the development of an unsteady axisymmetric supercavity, and the results were validated by a large amount of experimental data (Serebryakov, 2009). Based on the law of energy conservation, another version of the section equation without initial conditions was obtained by Logvinovich (2001), who better approximated a steady cavity by an ellipsoid; the same approach was applied to obtain the concrete form of the section equation (Vasin, 2002). In addition, a cavity model (Pellone et al., 2004) has been proposed for two-dimensional flows that takes into account the influence of added mass. It has also been found that gravity and lateral force on the cavitator influence the cavity shape to some extent, and in response to these problems, Logvinovich developed the formulas for deformations of cavity axis in uniform supercavitating flows using the momentum theorem, and successfully verified them through a series of experiments (Logvinovich, 1969). Zou et al. (2014) and Yu et al. (2012a) were inspired to model the effects of gravity, lateral force and inertial force on the maneuvering supercavity by the similar method, and simulated their maneuvering

* Corresponding author.
E-mail address: hopingzou@sjtu.edu.cn (W. Zou).

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motions in the vertical and horizontal planes, respectively. However, to study the maneuvering supercavity in actual unbounded flows, the plane model from our previous studies (Zou et al., 2014; Yu et al., 2012a) must be extended to three-dimensions so that it can serve to control and maneuver a supercavitating vehicle.

Hence, the effect of inertial force, induced by the pressure difference between the inside and outside surfaces of a supercavity along a trajectory, is first modeled in a moving coordinate system, and then in combination with effect models of gravity, lateral force and ocean waves, the supercavity is modeled for a three-dimensional maneuvering trajectory. Based on this model, a numerical algorithm is developed to simulate the maneuvering motion of a supercavity with an analysis of motion characteristics. To sum up, this paper makes important strides toward developing a maneuvering supercavitating vehicle model with control surface actuation and feedback control in complex flow conditions.

2. The maneuvering supercavity model

A supercavity is usually subject to the effects of control surface, gravity, inertial force and ambient pressure on the maneuvering trajectory, and is distorted accordingly. In this situation, internal pressure fluctuates and wave clearly appears on the cavity surface beyond the stability criterion (Paryshev, 2003). For a maneuvering supercavity, extreme unstability needs to be avoided or alleviated as much as possible, but this is difficult (Zou and Liu, 2015a). Assuming the gas in a supercavity is a perfect gas, the supercavity model consists of the cavity section equation, gas mass balance equation and effect model equations at given ventilation and gas-leakage rates, which together are a closed set of equations describing supercavity motion on the maneuvering trajectory.

2.1. Cavity section equation

As discussed in the Introduction, the cavity section equation was derived by several researchers using different methods to reveal the essence of Logvinovich's principle, respectively. Serebryakov's equation (Serebryakov, 2009) is applied for unsteady axisymmetric supercavity with universality as follows, in which initial conditions embody viscosity by empirical coefficients. It has proved to be very practical and effective by large numbers of unsteady experiments.

$$\mu(s)\frac{\partial^2 R_c^2(s,t)}{\partial t^2} + \frac{2\Delta p(s,t)}{\rho_w} = 0 \tag{1}$$

$$R_c^2(s,t)\Big|_{t=t_n(s)} = R_n^2(s),\quad \frac{\partial R_c^2(s,t)}{\partial t}\Big|_{t=t_n(s)} = R_n(s)V(s)\sqrt{\frac{2(C_d(s)-k(s)\sigma_c(s))}{k(s)\mu(s)}} \tag{2}$$

where $R_c(s,t)$ and $R_n(s)$ are the cross-sectional radii of cavity and cavitator on trajectory s at time t; ρ_w is the water density; $\Delta p(s,t)$ is the pressure difference between inside and outside the cavity, $\Delta p(s,t) = p_\infty(s,t) + p'(s,t) - p_c(s,t)$, where $p_\infty(s,t)$ is the ambient pressure, $p'(s,t)$ is the ambient perturbation pressure, and $p_c(s,t)$ is the internal pressure; $V(s)$ is the motion speed of the cavitator; $t_n(s)$ is the time when cavitation occurs; $\sigma_c(s)$ is the cavitation number; $C_d(s)$ is the cavitation drag coefficient; $k(s)$ is the assessment parameter for cavity maximal radius, taking into account small viscous losses; $\mu(s)$ is used for cavity length, characterizing the inertial properties of the cavity section as follows:

$$k = 1 - \frac{2\ \ln\frac{2}{\sqrt{e}}}{\ln\frac{4}{(1-M^2)\sigma_c}},\qquad \mu = \ln\frac{\lambda}{\sqrt{e}} \sim 0.5\ \ln\frac{1}{\sigma_c} \tag{3}$$

where M is the Mach number for subsonic flows and λ is the aspect ratio of the supercavity.

2.2. Gas mass balance equation

In Eq. (4), gas in a supercavity strictly obeys the conservation law of mass (Zou and Liu, 2015b), though cavity volume frequently changes with variations in gas supply and loss during maneuvering motions. Ocean temperature and waves are inevitable factors in actual unbounded flows, and have some effects on a supercavity. In our previous study (Zou and Liu, 2015a), these problems were discussed minutely, and the mass balance equation is as follows:

$$\frac{d}{dt}\left(\frac{p_c(s,t)(Q_c(t)-Q_b(t))}{T_c(s,t)}\right) \approx \frac{p_c(s,t)\dot{Q}_{in}(t)}{T_{in}(s,t)} - \frac{p_\infty(s,t)\dot{Q}_{out}(t)}{T_{out}(s,t)} \tag{4}$$

$$Q_c(t) = \int_{\tau_i}^{\tau_t}(S_c(s,t)-S_b(s,t))V(\tau)d\tau \tag{5}$$

where $Q_c(t)$ and $Q_b(t)$ are the volumes of the supercavity and inner body, respectively; $T_c(s,t)$, $T_{in}(s,t)$ and $T_{out}(s,t)$ are the temperatures in the supercavity, ventilation holes and tail; $\dot{Q}_{in}(t)$ and $\dot{Q}_{out}(t)$ are the volumetric flow rates of gas entering into and escaping from the supercavity; $S_c(s,t)$ and $S_b(s,t)$ are the cross-sectional areas of the cavity and enveloped body; τ_i and τ_t are the times of cavitation occurrence at the head and tail of the supercavity.

Concerning the effects of plane traveling wave (Zou and Liu, 2015a), the ambient perturbation pressure has the following form in infinitely deep flow fields:

$$p'(s,t) = a_w\rho_w g e^{-k_w h_w}\mathbf{C}(k_w x_w - \omega_w t) \tag{6}$$

where a_w, k_w and ω_k are the amplitude, number and circular frequency of the wave; x_w and z_w are the plane coordinates of the wave; h_w is the seabed depth; $\mathbf{C}$ is the abbreviation for the cosine function.

As a rule, ventilation rate is a principal control variable in real-world situations; hence any concrete formula is determined by practical background as a known parameter or a function of time (Wosnik and Arndt, 2009). In the case of the gas-leakage rate, however, great progress has been reported by Zou and Liu (2015a). The gas leakage of a supercavity at high speed is dominated by toroidal vortices; nevertheless, the gas-leakage mechanism needs to be further explored in connection with ventilation delay and the vehicle's afterbody piercing the cavity surface (Wosnik and Arndt, 2009). For now, Spurk's gas-entrainment model (Spurk, 2002) agrees relatively well with experiments (Savchenko and Savchenko, 2012) and numerical simulations (Kinzel et al., 2009) as follows:

$$\dot{Q}_{out}(t) = \frac{C_q C_{d0} V D_n^2(1+\sigma_c)}{\sigma_c}\sqrt{\frac{1}{\sigma_c}\ \ln\ \frac{1}{\sigma_c}} \tag{7}$$

where C_q is the coefficient dependent on the Reynolds number; C_{d0} is the drag coefficient at zero cavitation number; D_n is the cavitator diameter.

2.3. Effect equations

Due to the influences of gravity, lateral force on the cavitator and inertial force, some deviations of the cavity centerline from the maneuvering trajectory are inevitable in Fig. 1. It is worth emphasizing that it is reasonable to neglect the distortion of the cavity section during high-speed motion (Kirschner et al., 2002). Because the supercavity is relatively large in real-world applications, pressure