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Control of the ventilated supercavity on the maneuvering trajectory

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ABSTRACT

Dimension control of ventilated supercavity is the premise of realizing the controlling and maneuvering of supercavitating vehicle by regulating hydrodynamic distribution. The ventilation control system is modeled using control valve with equal percentage flow characteristic. Based on the control system model and the maneuvering supercavity model, the control algorithm is developed to dominate supercavity dimensions on the maneuvering trajectory. Control simulations are carried out using the algorithm, and control variables are evaluated. By means of Pearson correlation analysis, weights of control variables are quantitatively analyzed to propose the optimal control variable and control scheme. The algorithm is finally proved to be feasible by simulations.

1. Introduction

Supercavity has a great potential for significant drag reduction by almost fully enveloping its vehicle. Hence, many researchers take a close interest in it, and have made great progress in modeling and simulation of supercavitating flows. Especially, it has become possible to realize the controlling and maneuvering of supercavitating vehicle since it was found that supercavity can be formed by ventilation. However, control of supercavitating flows is the basis and guarantee of achieving the possibility as a research focus. It is a very complicated problem because various factors are involved and coupled, such as ambient flow, motion velocity, ventilation rate, and so forth. Besides, flow control has great effects on supercavity stability, and there exists certain contradictory relationship between them.

So far, some researchers have done some work on control of supercavitating flows. Some questions and potential methods were stated by Savchenko (2002) on the flow control. Arndt et al. (2005) also presented some perspectives and opportunities based on their previous experimental and numerical results. The air supply necessary for creating and maintaining cavity in steady and gust flows was studied experimentally in another paper (Arndt et al., 2009). Yu et al. (2013) proposed suction gas control methods of supercavitating flows, and verified their feasibilities and put forward an optimal control strategy by numerical simulations. Wosnik and Arndt (2009) carried out experiments on a semi-axisymmetric, ventilated supercavity and a single wedge-shaped, 45° swept, cavity-piercing fin. In their experiments, control surface-cavity interaction, cavity stability, hysteresis effects and fin lift with different angles of attack (AOAs) were studied, and closed-loop fin control for simple maneuvers were conducted. Khakpour and Yazdani (2005a, 2005b) analyzed aero boundary layer separation caused by pressure distribution in supercavity, and presented some approaches to control the separation. In the aspect of hardware, Kuklinski (2004) designed a supercavitation ventilation control system, including cavitator to form supercavity, control ring to adjust terminal end of supercavity and stop ring to regulate reentrant jet. A dynamic test platform was developed by Hjartarson et al. (2009) to evaluate control algorithms for supercavitating vehicle in water tunnel, and to validate and expand vehicle's force models.

Although research on control of supercavitating flows has made some progress, it is still in an exploratory stage, and has a long way to realize the control really in practice. It is an open big bottleneck problem to how to consider the relationship between controlling and stability of ventilated supercavity and alleviate their contradiction. Aiming to this question, the ventilation control system is modeled firstly, and then the control algorithm is developed to regulate supercavity dimensions in the maneuvering motion based on the control system model and the maneuvering supercavity model. Control simulations are carried out using the algorithm, and control variables are evaluated. Further, weights of control variables are quantitatively analyzed to propose the optimal control variable and control scheme by the method of Pearson correlation analysis, and the algorithm is confirmed as an effective method by simulations to some extent.

2. Maneuvering supercavity model

The ventilated supercavity is modeled on the maneuvering trajectory using the bubble dynamics method based on the

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Logvinovich's principle here. The model is different from ones embedded in N–S (Navier–Stokes) equations by defining fluid density, and has the flexible modeling and convenient calculation. It can be used to simulate unsteady supercavity, and then determine vehicle's hydrodynamic distribution as the premise of studying dynamics and control of the vehicle. More importantly, the model can be easily embedded into the dynamic and control model. The model is to build the most direct bridge between fluid dynamics and dynamics, control of supercavitating vehicle. Hence, it is of significance to develop the effective maneuvering supercavity model below.

Supercavity is usually subjected to ocean wave, deflection angle of cavitator and gravity on the maneuvering trajectory in unbounded flows besides the change of ambient pressure, and is easy to deform with bending axis under these effects. If gas in supercavity is regarded as perfect gas, basic equations, gas state equation and effect equations will constitute a closed set of equations at the given ventilation and gas-leakage rates, i.e., the maneuvering supercavity model. It is necessary to mention that these effect equations come from our previous published work.

2.1. Basic equations

Basic equations consist of expansion equation of supercavity section based on Logvinovich's principle and mass balance equation of gas, and can describe unsteady supercavity if ventilation and gas-leakage rates are given. The section equation (Vasin, 2002) was analytically given using the principle of conservation of energy on each continuous plane in an inertial reference frame. Serebryakov (1974, 1976, 2009) derived the equation with initial conditions for the prediction of unsteady axisymmetric cavity by asymptotic approach on the basis of the slender body theory. After that, the equation was derived by Logvinovich using a heuristic way based on the law integral conversation of energy, and his approach was approved by Vasin (2002). Besides, Pellone et al. (2004) also got the section model. The equation is used to predict unsteady slender axisymmetric cavity as follows:

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

where $S_c(\tau,t)$ is the cross sectional area of supercavity at time t, perpendicular to trajectory at the given point where cavitation occurs at time τ; $\Delta p(\tau, t)$ is the pressure difference between inside and outside of supercavity, $\Delta p(\tau,t) = p_\infty(\tau,t) + p'(\tau,t) - p_c(\tau,t)$, where $p_\infty(\tau,t)$ is the ambient pressure, $p'(\tau,t)$ is the ambient perturbation pressure, $p_c(\tau,t)$ is the internal pressure of supercavity; ρ_w is the water density; k satisfies $k = 4\pi C_d/a^2$ (Vasin, 2002), where C_d is the cavitation drag coefficient, $C_d = C_{d0}(1+\sigma_c)$, C_{d0} is the drag coefficient at zero cavitation number and usually taken as $C_{d0} = 0.82$ for disk cavitator, and σ_c is the cavitation number, a is a variable depending on cavitation number, expressed as $a = \sigma_c L_c/D_n$ for steady supercavity, L_c is the supercavity length, D_n is the cavitator diameter. The more exact estimation was given at high speed up to 1000 m/s by Serebryakov (1976).

For Eq. (1), initial conditions are

$$S_c(0) = \frac{\pi D_n^2}{4}, \quad \dot{S}_c = \frac{\pi C_d D_n V_\infty}{a} \tag{2}$$

where V_∞ is the motion velocity of cavitator in the inertial reference frame. Serebryakov (2009) also presented another very important initial condition in combination with his formulas, known as a modern presentation of the "Principle of independence of the cavity expansion".

The above equation expresses the known Logvinovich's principle of independent expansion of cavity section in the case of extended enough axisymmetric cavities. It is worth mentioning that the equation has presented in the paper (Serebryakov, 1974) for the first time. The equation has been derived in the frame of ideal fluid theory, and can take into account small viscosity influence with help of empirical coefficient in its initial conditions. It was repeatedly verified by many experiments, and also gave good results even at substantial distortions of axisymmetric cavity.

2.2. Improved gas mass balance equation

According to the principle of gas mass conservation in supercavity, the mass balance equation can be written as:

$$\frac{d}{dt}(\rho_g(Q_c - Q_b)) = \dot{m}_{in} - \dot{m}_{out} \tag{3}$$

where ρ_g is the gas density; Q_c is the supercavity volume; Q_b is the volume of the inner body in supercavity; $\dot{m}_{in}$ and $\dot{m}_{out}$ are mass flow rates of gas injecting into and escaping from supercavity, respectively.

Gas temperature in supercavity may be approximately equal to ambient temperature so that its effect on supercavity can be taken into consideration. Because gas speed is relatively high at ventilation holes behind cavitator, according to the Bernoulli equation, gas pressure in the region is slightly smaller than internal mean pressure. Also, tail directly touches external flows, and gas pressure approaches ambient pressure in the tail. Thus, Eq. (3) can be written approximately as follows:

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

where $\dot{Q}_{in}$ and $\dot{Q}_{out}$ are the volume flow rates of ventilated gas injecting into and escaping from supercavity; T_c, T_{in} and T_{out} are the temperatures in the supercavity, ventilation holes and tail closed region. The temperature is a function of water depth h, and approximately satisfies $T(h) = 18.61\exp(-0.88h)$ (water depth in kilometer) in the 170° west longitude of the Pacific Ocean (Yuan et al., 2007).

In the case of ventilation rate, it is usually regulated as a control variable with great flexibility in actual applications, so it is taken as a known parameter or a function of time determined by actual background. As for gas-leakage rate, Froude number, which describes gravity effect, is a key parameter of influencing its mechanism. According to effect extent, gas-leakage mechanism is divided into two modes: two vortex tubes and toroidal vortices. Epshtein (1971) systematically analyzed and described characteristics of these two different gas departures from cavity by experiments. Campbell and Hilborne (1958) and Buyvol (1980) proposed the transition criteria from the former to the latter, respectively, and experimental results showed that Buyvol criterion is more exact, ${\sigma_c}^{3/2}Fr^2 \geq 1.5$ where $Fr = V_\infty/\sqrt{gD_n}$. The former was usually observed as a steady character in water tunnel because of low Froude number (Kawakami and Arndt, 2011), and the corresponding mechanism was first modeled by Cox and Clayden (1956). Epshtein (1970) further discussed the phenomenon and presented the general semi-empirical gas-leakage formula. However, compared to two vortex tubes mechanism, toroidal vortices mechanism has not been well studied. In this case, supercavity keeps axisymmetric with negligible gravity effect, and is closed by unsteady reentrant jet. Assuming that gas is evacuated along shear layer of cavity surface to the tail, Spurk (2002) developed a gas entrainment model at high Froude number and validated the model by experiments of real vehicles. Besides, using computational fluid dynamics based on Navier-Stokes equations, the entrainment assumption was confirmed by Kinzel et al. (2009), and the similar behavior was also found in two-vortex supercavity. With supercavity in water tunnel as the research object, Zou et al. (2010) carried out numerical experiments to establish a gas-leakage model by defining velocity