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Motion Simulations of a Supercavitating Body with Variable Ventilations

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Abstract: Supercavitation drag reduction has been applied to greatly improve navigation speeds of underwater bodies. Ventilation in the flow separation area of the body's head is used to easily generate a supercavity, which is not limited by ambient pressure and motion speed. Besides, ventilation can be regulated to control supercavity shape for the supercavitating body's complicated motions. Due to the dynamic characteristics of ventilated supercavity and the control performance of ventilation, a change in ventilation influences the motion state of the body to varying degrees. Based on the dynamic model of the supercavitating vehicle (i.e., SCAV) in our work, the motions of the supercavitating body in a straight line are simulated under the changing ventilations. Analyses are made on the motion characteristics of the body in the motions. This study provides a theoretical basis for further research on the dynamic characteristics and motion stability of the ventilated supercavitating body in the maneuvering motion.

Keywords: supercavitating body; variable ventilation; dynamic model; algorithm; simulation

1. Introduction

Supercavitation achieves the purpose of drastically reducing drag by changing the density of the fluid attached to underwater body. Ventilation in the flow separation area on the body head can form and control supercavitation at different navigation speeds and water depths, which makes the supercavitation thoery and technology have a broader application prospect and provides a means to study supercavitation in water tunnel experiment[1,2]. Along with the continuous development of supercavitation research, it is important to control supercavitating flow pattern[3] or supercavity's macroscopic sizes[4] to ensure reasonable hydrodynamic forces for the body's maneuvering motions. In the supercavity shape control, ventilation is a key factor. It maintains supercavitation on the one hand, and needs to guarantee the supercavity dynamic stability on the other hand[5]. Supercavity usually changes with changes in ventilation, which affects the motion state and stability of the body. For maneuvering supercavitating bodies, these changes also have an effect on the performances of control surfaces, i.e., cavitator and fins. Therefore, based on the SCAV dynamic model with a control law presented in our previous work[6], the supercavitating body is simulated to analyze the motion characteristics during a straight horizontal navigation when ventilation changes.

2. SCAV Dynamic Model and Numerical Simulation Method

The SCAV longitudinal dynamic model is established based on the maneuvering supercavity dynamic model[7,8] that reflects the unsteady characteristics of supercavity, the influences of gravity and cavitator

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as a control surface. Based on the dynamic model, the control law is obtained using the exactly feedback linearization control method combined with LQR (linear quadratic regulator) control, and is embeded into the dynamic model. In our self-developed algorithm, the initial cavitation number is first estimated, and then is corrected by the supercavity internal pressure based on the supercavity dynamic model, and the fourth-order Runge-Kutta algorithm is combined to develop a motion simulation method for a maneuvering ventilated supercavitating body.

3. Results

The simulation process is described as: the body maintains a constant ventilation during the initial time period $t=[0.0,1.0]\mathrm{s}$, and then experiences ventilation disturbance during the time period $t=[1.0,3.0]\mathrm{s}$, and finally the disturbance disappears, the ventilation returns to its initial value and maintains for another $8.0\mathrm{s}$. Without loss of generality, it is assumed that the changes in ventilation are given in a simple and harmonic form, i.e., $\dot{Q}_{in}=\dot{Q}_{in0}(1+k_{in}\sin(\omega_{in}t))$, where $\dot{Q}_{in0}$ is the initial ventilation rate, k_{in} is the proportional coefficient of ventilation disturbance, ω_{in} is the circular frequency of ventilation disturbance.

The model parameters and initial flow field parameters are used in the literature[6] except the motion velocity $V=40\mathrm{m/s}$, initial cavitation number $\sigma_0=0.0759$ and initial ventilation coeffcient $\bar{Q}_{in0}=0.0124$ in the simulations. It is worth mentioning that the cavitation number is calculated based on the multi-fluid model of ventilated supercavitating flows[9] using the corresponding model parameters and flow conditions. Because the gravity influence index $\sigma_c Fr=2.2847$ is relatively small, where σ_c and Fr are the ventilated cavitation number and Froude number, respectively, gravity has a great influence on the supercavity[1,9]. Also, since the ventilation is equal to the gas entrainment amount in the initial steady flow state, the ventilation is estimated as $\bar{Q}'_{in0}=0.0104$ using Epstein's gas-leakage model[6,10,11]. There is not much difference between the estimated and calculated initial values at this case, so we use the proportional coefficient k_v=1.1923 between the two to modify the gas-leakage model, and then apply this modified model to the SCAV dynamic model.

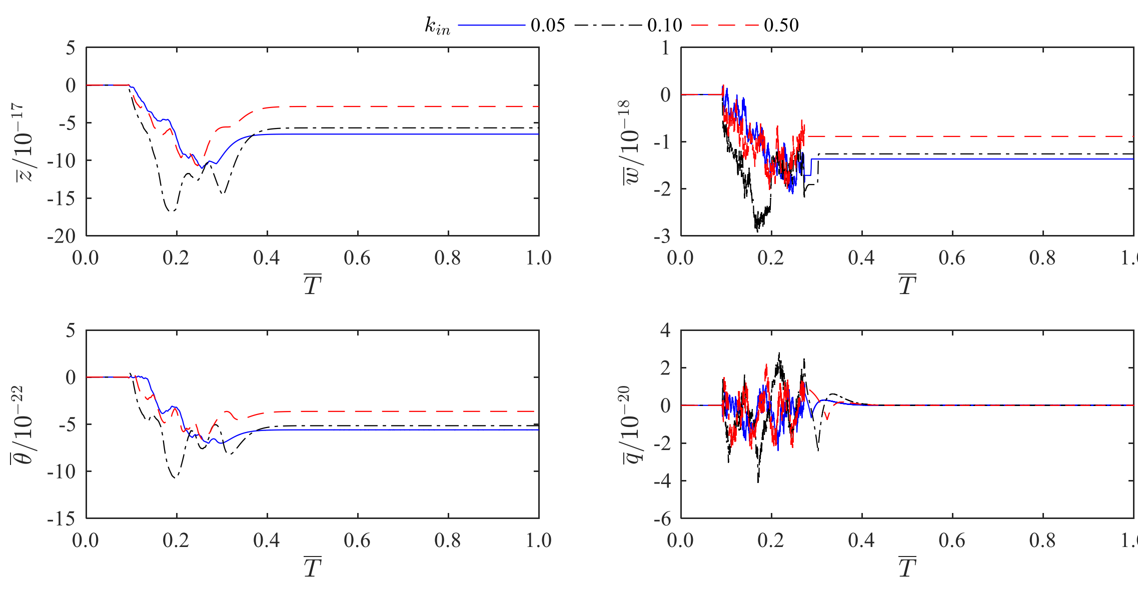

Figure 1. Motion state variables of the supercavitating body under different ventilation disturbnace amplitudes ($\omega_{in}=2\pi$)

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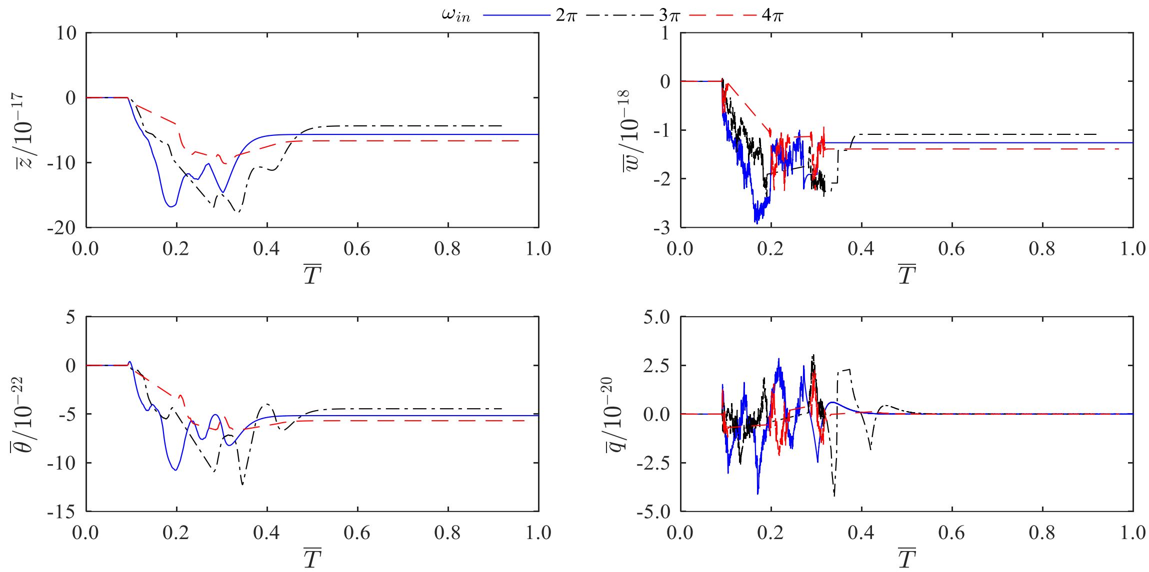

Figure 2. Motion state variables of the supercavitating body under different ventilation disturbnace frequencies ($k_{in} = 0.1$)

The amplitude and frequency of ventilation disturbance are changed to analyze the influence of ventilation change on the supercavitating body's motion state, respectively. It can be seen from the figures below that the vertical velocity $\overline{w}$ and the pitch rate $\overline{q}$ of the body are more sensitive to the disturbances than the vertical displacement $\overline{z}$ and pitch angle $\overline{\theta}$, $\overline{z} = z/D_n$, $\overline{w} = w/V$, $\overline{\theta} = \theta D_n/(VT)$ and $\overline{q} = qD_n/V$, where D_n and T are the cavitator diameter and the total motion time, $\overline{T}$ is the dimensionless time, $\overline{T} = t/T$. In the processes of disturbances, the motion states experience small pulsations, and then gradually make some transitions to stable states. Except for the pitch rate returning to zero, the other state variables are stable near their initial values. Under the same other conditions, the increases of the disturbance amplitude and frequency do not always aggravate the pulsations of the state variables due to the role of the control law, and the deviations of the final state also do not increases with the increases of the disturbances.

4. Conclusions

The initial state of the supercavitating body is determined by the numerical simulations based on the multi-fluid model of the ventilated supercavitating flows, and then the body's horizontal motions are simulated to analyze the influence of the ventilation disturbnaces on the motion state variables using the maneuvering SCAV dynamic model. Our future work is to combine the in-depth study of the shear-layer gas entrainment mechanism of the ventilated supercavity to study the complicated motions of the supercavitating body using the SCAV dynamic model.

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