Study on Effects of The Shape of Cavitator on Supercavitation Flow Field Characteristics

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Abstract. The cavitator is the key part of the nose of the vehicle to induce the formation of supercavity, which has an important influence in the cavity formation rate, cavity shape and cavity stability. To study the influence of the shape on the supercavitation flow field characteristics, the cavity characteristics and the resistance characteristics of different shapes of cavitator under different working conditions are obtained by combining technical methods of numerical simulation and experimental research in water tunnel. The simulation results are contrast and analyzed with the test results. The analysis results show that: in terms of the cavity size, the inverted-conic cavitator can form the biggest cavity size, followed by the disk cavitator, and the truncated-conic cavitator is the least; in terms of the cavity formation speed, the inverted-conic cavitator has the fastest cavity formation speed, then is the truncated-conic cavitator, and the disk cavitator is the least; in terms of the drag characteristic, the truncated-conic cavitator has the maximum coefficient, disk cavitator is the next, the inverted-conic cavitator is the minimal. The research conclusion can provide reference and basis for the head shape design of supercavitating underwater ordnance and the design of hydrodynamic layout.

1. Introduction

Supercavitation drag-reduction technology is a revolutionary drag-reduction technology, by which the underwater high-speed vehicle can get more than 90% drag-reduction and the underwater speed is greatly increased[1-2]. Based on the superiority of this technology, supercavitation drag-reduction technology has been widely used in the development of some new concepts and principles underwater weapons like supercavitating projectile, supercavitating torpedo, supercavitating submarine, among them the most representative is the shkval supercavitating torpedo of Russia and the U.S. airborne ultra cavitating ballistic missile system[3-4]. For supercavitating vehicles, the key is to form a stable supercavity around the vehicles, so that most of the surface of the vehicles is out of contact with the
water, thereby reducing the sailing drag force. How to efficiently generate supercavity is one of the key points in the research of supercavitation drag-reduction technology[5].

Cavitator is the key component to induce generating supercavity. The profile parameters of the cavitator have important influence on the formation speed, the shape and the stability of the supercavity[6-7]. In the early days, foreign scholars made a great deal of research on the hydrodynamic characteristics of the disk cavitator and conic cavitator. In terms of disk cavitator, Logvinovich established the function among cavitation number, cavitation diameter, cavitation resistance coefficient and the size of the bubble function through a large number of theoretical and experimental studies. In terms of conic cavitator, Savchenko established the coefficient of drag when the number of cavitation approaches to zero combined with extrapolation on the basis of experiments[8-9]. The domestic and overseas research are few for other hydrodynamic characteristics of the cavitator.

In order to approach a more comprehensive research on the supercavitating flow characteristics of different shapes of cavitator like disk, truncated-conic and inverted-conic, we analyzed the cavity formation speed, the cavity shape and the cavity hydrodynamic characteristics under different shapes of cavitator through numerical simulation and high speed water tunnel test. By comparison and analysis, the numerical simulation results are in good agreement with the experimental results.

2. Numerical simulation research

2.1 Computational model and simulation method

The computational model is aimed at different shapes of cavitator based on ICEM CFD and CFX. The shapes of three cavitators are showed in figure 1 with their computational domain and boundary conditions are showed in figure 2. In the modeling process, the computational domain is consistent with the water tunnel size which is $\phi 400 \times 2000 \text{mm}$. The distance between the flow surface of the model and the computational domain entrance is 300mm, which is consistent with the model installation position. Boundary condition setting is: The entrance of the calculation domain is the speed entrance, and the water speed is the experimental water speed, which are 6m/s and 8m/s respectively; the outlet calculation domain is the pressure exit, which is 1atm; the computational domain is surrounded by solid walls; the front part of the cone is opened with an annular air inlet, which is set to quality entry. The ventilation medium is incompressible gas, and the volume flow rate is 40SLPM. The enlarged conical section at the back of the model coincides with the test.

![Figure 1: The shapes of three cavitators](image1)

![Figure 2: computational domain and boundary conditions](image2)
Numerical grid uses the O shape mesh technique of ICEM CFD to generate hexahedral structured mesh, the final total mesh number is 200 thousand, and the grid quality is well evaluated. The numerical simulation process use the Unsteady Orado phase flow model, aiming the liquid and gas phases the equations of flow are solved and the influence of gravity and the cavity surface tension are considered. The gravity direction is set along the negative direction of the Y axis. The momentum transfer between the bubbles is achieved by setting drag coefficient, and the drag coefficient is set to 0.44. According to the literature recommendation, the SST model has good robustness in turbulence model simulation, and the convergence is better than the classical turbulence model. The SST turbulence model is selected for both gas and liquid phases. The high precision difference scheme is adopted in the calculation, and the automatic step is adopted in the iteration at the same time step. By calculation, it about spends 100ms from the start of ventilation to the cavity stabilization.

2.2 Numerical simulation results
Through numerical simulation of different shapes of cavitator, the cavity shape, cavity development process and the drag characteristics of different cavitator shapes under different velocity conditions are obtained.

Fig.3~Fig.5 respectively shows the stable shape of cavity of different cavitator shapes under different velocity. From the figure we can see the cavity under the working condition of 8m/s water velocity is little bigger than that under 6m/s. At the same time, due to the gravity, the cavity has obvious drift phenomenon, and with the increase of the cavity length, the greater the drift of the cavity is. From the size of the cavity, the inverted-conic cavitator can form the biggest cavity size, followed by the disk cavitator, and the truncated-conic cavitator is the least.

![Figure3: The simulation result of truncated-conic cavitator](image)

![Figure4: The simulation result of disk cavitator](image)
Fig. 5: The simulation result of inverted-conic cavitator

Fig. 6–Fig. 8 respectively shows the cavity developing process of different shapes of cavitator. From the figure we can see, from the ventilation start it takes 91 ms for truncated-conic cavitator to generate stable cavity; it takes 131 ms for disk cavitator to generate stable cavity; it takes 71 ms for inverted-conic cavitator to generate stable cavity. In terms of the cavity formation speed, the inverted-conic cavitator has the best cavity formation performance, then is the truncated-conic cavitator, and the disk cavitator has the least speed of formatting cavity. The stability time of the disk cavitator is almost twice as much as the truncated-conic cavitator.

Fig. 6: The cavity development process of truncated-conic cavitator
3. **Experimental study**

3.1 **Test model and test method**

Aimed at the three different shapes of cavitators, three test models are designed as shown in Fig. 9. The experiment was carried out in the high-speed water tunnel of Northwestern Polytechnical University. The test model is fixed in the working section of the high-speed water tunnel in a tail support manner, and the hollow strut in the ventilation pipe ventilate to the venthole of the head of the test model, then the supercavity is formed. Three point force balance is installed in the hollow strut, connected to the model by a support bar to test the drag of the test model, as shown in Fig. 10. In the test, after the stable supercavity is formed, the test system is opened, the output information of the force balance is collected, and at the same time the supercavity shape image is taken.
3.2 Test result

Based on the experimental study of different shapes of cavitator in high-speed water tunnel, the experimental data of cavity shape and drag characteristics of different cavitator shapes under different velocity is obtained.

Fig.11~Fig.13 are respectively the cavity shape of different cavitator shape under different velocity. It can be seen from the figure that different shapes of cavitator under 6m/s, 8m/s water velocity’s working condition can all get stable and transparent cavity, but because of gravity, the cavity is slightly asymmetric. For the same cavitator, the cavity under the working condition of 8m/s water velocity is little bigger than the cavity under 6m/s. As shown in Table 1, under the same working condition, the inverted-conic cavitator can form the biggest cavity size, followed by the disk cavitator, and the truncated-conic cavitator is the least. At the same time, the test also found that under the same working conditions, the inverted-conic cavitator is easier to form cavity.

Figure 11: The test result of truncated-conic cavitator
Water velocity = 6 m/s
Water velocity = 8 m/s

Figure 12: The test result of disk caviterator

Water velocity = 6 m/s
Water velocity = 8 m/s

Figure 13: The test result of inverted-conic caviterator

### Table 1: The drag coefficient of different shapes of cavimators in the test result

| The shapes of cavimator | Drag coefficient |
|-------------------------|------------------|
|                          | Velocity=6m/s   |
|                          | Velocity=8m/s   |
| Truncated-cone           | 1.22             |
| Disk                     | 1.19             |
| Inverted-cone            | 1.12             |

4. Comparison and analysis of results

4.1 Comparison and analysis of the cavity shape

Numerical simulation and the high-speed water tunnel test have obtained the cavity shape under the established water velocity and ventilation volume. By comparison, it can be seen that under the same shape of cavimator and working conditions, the numerical simulation is basically consistent with the cavity shape obtained by high-speed water tunnel test. Fig.14 shows the cavity shape contrast chart of disk cavimator under the velocity of 6 m/s. Fig.15 shows the cavity shape contrast chart of inverted-conic cavimator under the velocity of 8 m/s. Under the same scale condition, the cavity length of the numerical simulation is basically consistent with the test.

Figure 14: The cavity shape contrast of disk cavimator under the velocity of 6 m/s
Figure 15: The cavity shape contrast of inverted-conic cavitation under the velocity of 8m/s

4.2 Comparative analysis of drag coefficients

Table 2 is a comparison of the drag coefficients of different shapes of cavitators under different working conditions, from which we can see, the drag characteristic variation low obtained by numerical simulation of different shapes of cavitators are basically consistent with the high-speed water tunnel test. Under the same working conditions, the drag coefficient obtained by the high-speed water tunnel test is a little bigger than which obtained by numerical simulation results. The error of numerical simulation is less than 10%.

| The shapes of cavitator | CFD result | Test result | Relative error |
|-------------------------|------------|-------------|----------------|
|                        | 6m/s       | 8m/s        |                |
| Truncated-cone          | 1.10       | 1.16        | 7.7%           |
| Disk                    | 1.07       | 1.19        | 10%            |
| Inverted-cone           | 1.03       | 1.12        | 8%             |

5. Conclusion

In this paper, aiming at different cavitator supercavitation flow field, the numerical simulation and experimental investigation are carried out. The cavitation characteristics and drag characteristics of different shapes of cavitators are obtained by the two methods. The conclusions are as follows:

(1) The cavitation characteristics and drag characteristics obtained by numerical simulation and high-speed water tunnel test are basically the same, and the law of variation is also basically the same. The calculation results and test results are quite credible.

(2) The three shapes of cavitators all can form stable and transparent cavity at 6m/s and 8m/s velocity conditions. In terms of the cavity size, the inverted-conic cavitator can form the biggest cavity size, followed by the disk cavitator, and the truncated-conic cavitator is the least; in terms of the cavity formation speed, the inverted-conic cavitator has the fastest cavity formation speed, then is the truncated-conic cavitator, and the disk cavitator is the least.

(3) Under the same working condition, among all the three shapes of cavitators, the truncated-conic cavitator has the maximum coefficient, disk cavitator is the next, the inverted-conic cavitator is the minimal.

The study results of this paper can provide references and basis for the head shape design and hydrodynamic layout of the supercavitating underwater vehicles, especially for the underwater weapon such as supercavitating torpedoes, supercavitating projectiles and underwater bullets.
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