An experimental study on characteristics of cavitation and ballistic of axisymmetric slender body underwater movement

Cheng-Gong Zhao, Cong Wang, Ying-Jie Wei, Xiao-Shi Zhang

School of Astronautics, Harbin Institute of Technology, Harbin 150001, China

E-mail: cgzhhhit@gmail.com

Abstract. An experimental study of the axisymmetric slender body underwater movement was conducted using high-speed photography technology. From the results of the experiment, the characteristics of cavitation and ballistic of the axisymmetric, including the formation, development, evolution and collapse of the cavity, are presented in the paper. The experimental results show that the axisymmetric slender body moves in a supercavity, and the slender body rotate in the supercavity on its head at the same time due to the perturbation of launching. The supercavity wall is transparent and smooth except the tail itself. The impact between the tail of slender body and supercavity wall resulted from the slender body’s rotation is termed as tail-slap which is one way to keep the stabilization of the movement. Series of different flow mechanisms and the relationship between ballistic characteristics and cavity characteristics with different initial velocities are discussed. The slender bodies have different accelerations and ballistics with different initial velocity which means they have different drag forces.

1. Introduction

Cavitation occurs in a variety of high-speed hydrodynamic systems where the absolute local pressure controlled by the flow hydrodynamics drops below the liquid saturation pressure. Cavitation is usually harmful for hydraulic machinery because it may cause material damage and force surge, etc. However, the recent research results show that the supercavitation is beneficial to reduce the skin-friction drag of the slender body travelling underwater which in turn enlarge the travelling range of the slender body [1]. The supercavitating hydrodynamics have great influence on the ballistic characteristics and structure dynamics of slender body [2].

The early research of the supercavitating problems focus on the derived analytical form of supercavitation. P. R. Garabedian studied the calculation of axisymmetric cavities [3]. A study by May focused on the variation of cavities during water entry of slender body [4-6]. Studies by Ruzzene and Edward[7,8] focused on the static and dynamic analysis of projectiles underwater movement. While Hrubes captured the high-speed supercavitating images using high-speed imaging technology [9]. In addition, Fabien Petitpas carried out the experiment of spherical projectiles underwater movement [10].

This paper describes design, setup and testing of a laboratory experiment for studying the cavity and ballistic characteristics of a high-speed free-flying slender body underwater. Moreover the paper compares the differences of cavity and ballistic characteristics with the different initial cavitation number \( \sigma = \frac{2(p - p_v)}{\rho v^2} \), where \( p \) is the reference hydrostatic pressure, \( p_v \) is the vapor pressure, and \( \rho \) is the mass density of the fluid.
2. Experimental setup and model of slender body
The schematic of the experimental facility of the slender body underwater movement is shown in Figure 1. The experimental facility consists of four parts: (1) a horizontal launch system; (2) water tank; (3) protection and recycle system; (4) measurement system. The water tank consists of opening top and stalinite on both sides and steel plates in rest and the scale of 1.2m×1.2m×10m. The launch system is composed of a vessel within compressed nitrogen, light gas gun and trigger. The measurement system is a FASTCAM SA6 high speed camera illuminated by 6×1300W halogen lamps.

![Figure 1. Schematic of the experimental facility of the slender body underwater movement](image1)

Figure 2 shows the experimental facility and model of slender body with its adapter. The model of slender body is combination of truncated cone and cylinder afterbody. The diameters of the flat head and afterbody cylinder are \(d=4\)mm, respectively, and the length of the slender body is 170mm. The semi-cone angle is 4 degrees. The material of the slender body is steel. The dimension of the slender body is as shown in Figure 3.

![Figure 2. (a) Experimental facility (b) Model of slender body and adapter](image2)

![Figure 3. Dimension of the slender body](image3)

The slender body loaded in the adapter was fired horizontally into the water tank. Concurrently, the high speed camera was recording the supercavitation of slender body and its trajectory. We obtained different initial velocity and cavitation number by adjusting the pressure in the chamber of the light gas gun.

3. Experiment results and discussions
The coordinate system \(x-O-y\) used in the paper is shown in Figure 1. The \(x\)-axis is in direction of horizontal and \(y\)-axis is in direction of vertical.
3.1. Cavity characteristics

Figure 4(a) shows the supercavitation of the slender body at the initial cavitation number $\sigma=0.0044$ ($v=212.1\text{m/s}$). The supercavitation develops from the edge of the flat head of the slender body and expands along the trajectory of the flat head's centre. The wall of the supercavitation is smooth and transparent except for the contact area which can be attributable to the rotation of the slender body in the supercavitation. Figure 4(b) shows the details of the wall of supercavitation.

Figure 4. (a) Characteristics of cavity at time $t=3\text{ms}-7\text{ms}$ (b) Profile of the supercavitation

Figure 5 shows the closure and shedding of the cavity at the initial cavitation number $\sigma=0.0044$ ($v=212.1\text{m/s}$) at different times. The water vapor in the afterbody of the supercavitation is condensed at some extent by the high pressure caused by the severe re-entrant jet. Observe in Figure 5 that, there is mixture of water vapor and water in the tail of the supercavitation. The shedding of the vapor-water mixture produces the vortices which disappear in the flow field downstream. The number of shedding vortices decreases over time from $t=18\text{ms}-22\text{ms}$ in Figure 5 and the vibration decreases too. The decrease of the number of shedding vortices is due to the decrease of evaporation rate caused by the reduction of the slender body’s velocity.

Figure 5. Closure and shedding of the cavity at time $t=18\text{ms}-22\text{ms}$

Figure 6. The variations of slender bodies with different initial cavitation numbers

3.2. Ballistic characteristics

Three tests are conducted in the paper which have different initial cavitation number. Marked as follows:

Test a: the initial velocity of the slender body is $104.1\text{m/s}$, initial cavitation number is 0.0181;
Test b: the initial velocity of the slender body is $193.7\text{m/s}$, initial cavitation number is 0.0052;
Test c: the initial velocity of the slender body is $212.1\text{m/s}$, initial cavitation number is 0.0044.

The variations of the velocity of slender body versus time with different initial cavitation number are shown in Figure 6. As can be seen in Figure 6, the decay rates of slender bodies with different initial cavitation number are different. The decay rates of test b and test c are high than that of test a because of the differences in initial cavitation numbers.
Figure 7. Trajectories in x direction versus time with different initial velocities

Figure 8. Trajectories in y direction versus time with different initial velocities

Figure 7 and 8 show the displacements of the slender bodies in x-direction and y-direction, respectively. The effect of gravity is negligible because the initial force is greater than gravity when the slender body travel in a high-speed.

4. Conclusions
The experiment of supercavitating slender body travelling underwater have been presented in this paper. Section 2 focused on the setup of the experiment and model of the slender body. Section 3 presented the results of the experiment, including closure and shedding of cavity, and ballistic variation of slender body. A discussion of results shows that there is a high-pressure area in the tail of the supercavity due to the severe re-entrant jet of the supercavity. In addition, the shedding of the vapour-water mixture produces the vortices which disappear in the flow field downstream.

Acknowledgements
The authors would like to acknowledge the financial support of the Fundamental Research Funds for the Central Universities of Ministry of Education of China (Grant No. HIT.NSRIF.201159)

References
[1] Savchenko Y N 2001 VKI Special Course on Supercavitating Flows (Brussels: St. Joseph Ottawa/Hull) p313
[2] May A 1975 AD-A020 429
[3] Garabedian P R 1955 Pac. J. Math 6 611
[4] May A, Woodhull J C 1948 J. Appl. Phys. 19 1109
[5] May A 1951 J. Appl. Phys. 22 1219
[6] May A 1979 J. Hydrodynamics 4 140
[7] Ruzzene M 2004 Comput. Struct. 82 257
[8] Alyanak E, Venkayya V, Grandhi R, Penmetsa R 2005 Finite Elem. Anal. Des. 41 563
[9] Hrubes JD 2001 Experiments in Fluids 30 57
[10] Fabien P, Jacques M, Richard S, Emmanuel L, Laurent M 2009 International Journal of Multiphase Flow 35 747