The Numerical Simulation of the Vertical Water Entry Process of High Speed Projectile with Small Angle of Attack

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Abstract. Based on the numerical simulation method, the high speed vertical water entry process of projectile moving at 1000m/s with small angle of attack is studied. By analyzing the cavity configuration and hydrodynamic characteristics of the process, the influences of the small entry angle on the water entry stability process are obtained. The simulation results indicate that the projectile's ballistic can achieve relative stable state when the water entry angle is less than 0.5°, otherwise the water entry cavity can be pierced by tail fin. The pierced size tend to increase with the increased water entry angle as well as the projectile's ballistic become unstable. In addition, the rotation of the projectile owing to pitching moment has little effect on cavity configuration and water entry stability.

Keywords: Projectile, water entry angle, water entry cavity, stability.

1. Introduction

Supercavitating projectile weapon is a kind of weapon system which can hard kill underwater targets such as mines, torpedos and frogmans by firing supercavitating projectile through artillery. The projectile is launched by the gun, flies through the air and enters the water, then passes through the initial water entry trajectory and underwater supercavitating trajectory until it hits the target [1, 2].

The water entry process of high-speed projectile includes flow phenomena such as crossing free surface, phase change and turbulence [3, 4]. At present, most researches at home and abroad on projectile water entry are in the low speed range, so it is very important to carry out high-speed water entry research [5, 6]. In this paper, numerical simulation method is used to study the vertical entry process of high-speed projectile. Taking the water entry angle of attack as a single variable, the numerical simulations of multiple working conditions are carried out. The cavity shape and hydrodynamic characteristics of the vertical water entry process are analyzed, and the influence of the angle of attack and rotation angle of projectile on the vertical water entry process are discussed.
2. Establishment and validation of high speed water entry model

2.1. Establishment of high speed water entry model

2.1.1. Basic Governing equations. The The VOF homogeneous multiphase flow model can describe the multiphase flow formed by air, steam and water, and the fluid control equation describing the water entry process is established. Neglecting the thermal effect in the process of entering water, the volume fraction of liquid phase, gas phase and steam phase in the unit are calculated. The volume fraction of each phase satisfies the equation (1). \( \alpha_l, \alpha_v, \alpha_a \) are the volume fractions of liquid phase, water vapor phase and gas phase respectively.

\[
\alpha_l + \alpha_v + \alpha_a = 1
\]  

(1)

The continuity equation of mixed medium is as follows. \( u_i \) is the velocity component, \( i = 1, 2, 3 \), the same as below.

\[
\frac{\partial \rho_m}{\partial t} + \frac{\partial (\rho_m u_i)}{\partial x_i} = 0
\]

(2)

The momentum conservation equation is as follows:

\[
\frac{\partial (\rho_i u_i)}{\partial t} + \frac{\partial (\rho_i u_i u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \mu_t \right) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \frac{\partial \rho_p}{\partial x_i}
\]

(3)

And the expressions \( \rho_m \) and \( \mu_m \) are as follows:

\[
\rho_m = \alpha_l \rho_l + \alpha_v \rho_v + \alpha_a \rho_a
\]

(4)

\[
\mu_m = \alpha_l \mu_l + \alpha_v \mu_v + \alpha_a \mu_a
\]

(5)

The transport equation of air phase volume fraction is as follows:

\[
\frac{\partial \alpha_a}{\partial t} + \frac{\partial (\alpha_a u_i)}{\partial x_i} = 0
\]

(6)

2.1.2. Turbulence Model. The standard \( k - \varepsilon \) model is a two equation turbulence model. When the model is used to simulate flow, the characteristic length and velocity need to be solved. \( k \) is the fluctuating kinetic energy of turbulence, and \( \varepsilon \) is the dissipation rate corresponding to the fluctuating kinetic energy of turbulence. The length and time scale of turbulence increase with the increase of \( k \) value, and both decrease with the increase of \( \varepsilon \) value. \( k, \varepsilon \) can be obtained from equations (7) and (8).

\[
\frac{\partial (\rho_k)}{\partial t} + \frac{\partial (\rho_k u_i)}{\partial x_i} = P - \rho\varepsilon + \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + P_{kB}
\]

(7)

\[
\frac{\partial \rho \varepsilon}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{C_1 \varepsilon \rho k}{k} \frac{\partial u_i}{\partial x_j} - \frac{C_2 \rho \varepsilon^2}{k} + \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + P_{kB}
\]

(8)
In the formula, $C_1 \varepsilon = 1.44$, $C_2 \varepsilon = 1.92$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$. $P_{kb}$ and $P_{\varepsilon b}$ are the turbulent kinetic energy term caused by buoyancy.

### 2.1.3. Cavitation Model

The Schnerr and Sauer cavitation model can be used to simulate the cavitating flow around the projectile in the water entry process. The model relates the volume fraction of vapor phase with the number of bubbles per unit volume of fluid. The expression of the model is as follows. Where, $\rho_w$ is the water density, $\alpha_c$ is the volume fraction of gas core, $R_B$ is the diameter of gas core cavity and $n$ is the number of bubbles per unit volume.

\[
\begin{align*}
\dot{m}^* = \frac{\rho \rho_w}{\rho_c} (1 - \alpha_c) \left( \frac{2}{3} \frac{p - p_c}{p_c} \right) ^{1/3} & \quad p < p_c, \\
\dot{m}^* = \frac{\rho \rho_w}{\rho_c} (1 - \alpha_c) \left( \frac{2}{3} \frac{p - p_c}{p_c} \right) ^{1/3} & \quad p > p_c.
\end{align*}
\]

\[R_B = \left( \frac{\alpha_c}{1 - \alpha_c} \frac{3}{4\pi n} \frac{4}{3} \frac{\pi R_B^3 N_B}{2} \right) ^{1/3}, \quad \alpha_c = \frac{4}{3} \frac{\pi R_B^3 N_B}{1 + \frac{4}{3} \pi R_B^3 N_B}
\]

### 2.1.4. The solution of control equation

The finite volume method is used to discretize the governing equations in time and space. The coupling solution of pressure field and velocity field adopts PISO algorithm; the spatial discretization of pressure field adopts PRESTO! Scheme; the discretization of momentum equation adopts first-order upwind scheme; the discretization of volume fraction of each phase adopts cicsam scheme.

### 2.2. Validation of high speed water entry model

Guo Zitao et al. [7, 8] conducted an experimental study on the water entry process of projectile at the velocity of 603 m/s. In this paper, the above experimental process is numerically simulated, and the simulation results are compared with the experimental images, as shown in Figure 1. It is found that the numerical simulation results of the cavitation development process of the vehicle in the water are quite consistent with the experimental results, which verifies the accuracy of the numerical simulation of the high-speed water entry process.

![Figure 1. Comparison of experimental and numerical results](image)

### 3. Analysis of numerical simulation results

The three-dimensional model of the projectile is shown in Figure. 2, with a length of 180mm, a diameter of 15mm, a cavitator diameter of 4mm and a total weight of 120g. The mesh generation corresponding to the numerical simulation of the water entry process is shown in Figure 3. The local refinement is carried out around the projectile [9, 10]. In the numerical simulation, the initial velocity of projectile entering water is 1000 m/s, and the research range of angle of attack is 0° to 1.5°.
3.1. Analysis of cavity shape in vertical water entry at 0 angle of attack

Take the longitudinal plane passing through the elastic axis as the research plane, the contour of the two-phase volume fraction (liquid phase on the left and water vapor phase on the right) in the process of vertical water entry at 0 angle of attack is shown in Figure 4. The results show that with the increase of water depth, the cavity near the projectile wall becomes larger and the thickness of the cavity becomes thicker. The water vapor increases with the formation of the cavity, almost full of the cavity, and only a little air is brought in at the tail of the projectile.

The development of cavity shape in the process of projectile vertical entry into water is shown in Figure 5. The conical surface and cylindrical surface are always in the water entry cavity without being wet. When the tail enters the water, the water surface turbulence is obvious and the wing surface touches the water. After the whole projectile enters the water completely, the tail is basically wrapped in the cavity, and the shape of the cavity is stable.

3.2. Analysis of cavity shape in vertical water entry at small angle of attack

The volume fraction comparison of liquid phase and water vapor phase in small angle of attack is shown in Figure 6. Among them, A1, B1 and C1 are the liquid phase volume fraction corresponding to 0.5 °, 1 ° and 1.5 ° water entry attack angles respectively; A2, B2 and C2 are the water vapor phase volume fraction corresponding to 0.5 °, 1 ° and 1.5 ° water entry attack angles respectively. With the existence of the angle of attack, the size of the cavity on both sides of the projectile is no longer the same, and the size difference between the two sides increases with the increase of the angle of attack. The water vapor in the left bubble increases correspondingly, but the air intake does not increase significantly.

The comparison of cavitation shapes of small angle of attack in vertical entry is shown in Figure 7. Among them, A, B and C correspond to 0.5 °, 1 ° and 1.5 ° angle of attack in water entry respectively.
The cavity has been punctured by the tail in varying degrees. The greater the angle of attack is, the greater the puncture degree is. The results show that there were only frontal puncture vacuoles in the tail of A, and the puncture degree of B and C was 1/4 wing height and 1/2 wing height respectively.

3.3. Analysis of cavity shape in vertical water entry at 0 angle of attack

The resistance curve of vertical water entry at 0 angle of attack is shown in Figure 8. The analysis shows that there will be two impact peaks in the process of water entry due to cavitator and tail, and the resistance coefficient is 4.9 and 1.3 respectively. After these two resistance mutations, the resistance coefficient gradually approaches 0.90. It shows that the tail fin does not puncture the cavity after the projectile is completely flooded.

3.4. Analysis of cavity shape in vertical water entry at small angle of attack

The resistance curve of vertical water entry at small angle of attack is shown in Figure 9. Corresponding to the water entry process at 0.5°, 1° and 1.5° angles of attack, the peak values of resistance coefficient of cavitator are 4.88, 4.86 and 4.85 respectively.
The comparison curve of lift coefficient for vertical entry at small angle of attack is shown in Figure 10. Compared with the peak value of the resistance coefficient, the peak value of the lift coefficient is less than 0.3 at 0.5°, 1° and 1.5° angles of attack. In the stage of tail entering water, the fluctuation of lift coefficient is larger than that of cavitator entering water and it increases with the increase of angle of attack. The main reason for the poor stability of the water entry trajectory is the larger lift of the whole projectile after entering the water at 1° and 1.5° attack angles.

The pitching moment coefficient curve of vertical water entry at small angle of attack is shown in Figure 11. The cavitator enters the water to produce overturning moment. When the tail enters the water the tail and cylinder surface pierce the cavity to produce the restoring moment, and the restoring moment is proportional to the water entry angle of attack. The moment makes the projectile rotate in the longitudinal plane.

From the rotation theorem of angular momentum, The rotation angle can also be said to be the pitch angle, and the expression can be obtained as follows. Where, $J$ is the moment of inertia of projectile; $M$ is the pitching moment of projectile. By integrating the pitching moment in equation (11), the pitch angle variation curve of projectile can be obtained, as shown in Figure. 12. The projectile pitch angle increases with the increase of the water entry angle of attack.

$$
\delta = \frac{1}{J} \int \int M dt
$$

The pitch angle after the projectile entering the water under different angles of attack are shown in Table 1. It can be seen that under the conditions of 0.5°, 1° and 1.5° water entry angles of attack, the projectile body rotates slightly during water entry, and the angles of attack of the whole projectile after
water entry are $0.477^\circ$, $0.9515^\circ$ and $1.364^\circ$ respectively. This shows that the rotation of the projectile makes the angle of attack decrease slightly, the piercing degree of the tail decreases correspondingly, and the stability of the water entry trajectory is enhanced.

Table 1. Corresponding table of angle of attack and pitch angle

| Nominal angle of attack | pitch angle | Actual angle of attack |
|-------------------------|-------------|------------------------|
| 0.5                     | -0.023      | 0.477                  |
| 1                       | -0.049      | 0.951                  |
| 1.5                     | -0.136      | 1.364                  |

4. Conclusions

Through numerical calculation, the following conclusions are obtained. The results can provide a reference for the study of water entry stability of high-speed projectiles.

(1) When the angle of attack is less than 0.5 degrees, a complete water entry cavity can be formed and the water entry trajectory is stable.

(2) When the angle of attack increases to a certain extent, the phenomenon of tail puncture cavity occurs, and the degree of puncture increases with the increase of angle of attack, and the stability of water entry trajectory decreases.

(3) The angle of attack is the main factor affecting the stability of water entry trajectory. The projectile rotation can be regarded as the passive response to reduce the interference of angle of attack, which is beneficial to enhance the stability of water entry trajectory.

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