Impact characteristics and strength evaluation of a slender body obliquely entering water at high speed

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Abstract—Based on Coupled Eulerian-Lagrangian method, the impact characteristics and strength evaluation of high speed multi-angle oblique water entry of slender body were studied. In order to solve the complex fluid-structure coupling problem and large deformation problem, the Lagrangian grid is used to divide the slender body structure grid, and the Euler grid is used to divide the fluid grid, the effectiveness of the method is verified by comparing with the experimental results. Furthermore, by simulating the impact process of multi-angle water entry, the time-history curves of acceleration, stress and strain at the head position of the slender body were analyzed, and the strength evaluation was carried out to verify the structural safety combined with the residual strength formula. The results show that there is a positive correlation between the impact load and the water inlet angle, and the larger the water inlet angle, the greater the impact load; the residual strength factor of the slender body is positive at 15° and 20°, and the structure is safe, at 30°, the residual strength factor is -0.203, and the structure is unsafe.

1. Introduction
The problem of water entry impact is a complex physical problem of solid, liquid and gas three-phase coupling\textsuperscript{[1]}, in the process of cavitation generation, gas-liquid phase change is also involved, which is strongly nonlinear, coupled and unsteady\textsuperscript{[2]}. Amphibious aircraft\textsuperscript{[3]}, air-dropped torpedoes\textsuperscript{[4]}, spaceship return capsule\textsuperscript{[5]} are all problems of water impact, the structure will produce huge impact load at the moment of entering water, and entering water across the medium will form annular cavitation around the movement trajectory of the structure, this places high demands on the structural strength of the impactor. The problem of water impact is very complex and systematic, and theoretical analysis is not enough to solve it. Compared with theoretical methods and experimental methods, numerical simulation has the advantages of low cost, intuition, and strong repeatability. Many scholars use Volume of Fraction (VOF) multiphase flow model\textsuperscript{[6]}, Arbitrary Lagrangian-Eulerian (ALE) method\textsuperscript{[7]}, Smoothed Particle Hydromechanics (SPH) method\textsuperscript{[8]} and other numerical methods to carry out numerical research on water impact.

This paper establishes high-speed water impact model based on CEL method, and the effectiveness of numerical method is verified by water entry test. Compared with the experimental results, the effectiveness of the method is verified. By simulating the impact process of multi-angle water entry, the time-history curves of acceleration, stress and strain at the head position of the slender body were analyzed, and the strength evaluation was carried out to verify the structural safety combined with the residual strength formula.
2. Numerical simulation method

The problem of gas-liquid-solid three-phase coupling is involved in the entry of slender bodies into water, using CEL (Coupled Eulerian-Lagrangian) method to solve complex fluid-structure coupling problems and large deformation problems. The CEL method effectively combines the Lagrangian method and the Euler method. Lagrange method is used to divide the structure grid and Euler method is used to divide fluid grid, the finite difference method is used to solve two-dimensional fluid dynamics problems with moving boundaries, and recalculates the physical quantities such as mass. In the Euler method the grid is fixed and the material transport is carried out between the Euler grids, the flow trajectory of the material in the grid is calculated by EVF (Eulerian Volume Fraction) in each element. Based on the principle of Immersed boundary method, the kinematic and fluid-structure interaction analysis of Lagrange element in Euler element is established, and carries out the coupling solution.

In the simulation of water entering process, water medium flow is regarded as approximately incompressible and viscous laminar flow, the volume response is described using the Mie-Grüneisen equation of state in linear Us-Up Hugoniot form. The common form is:

\[ p - p_H = \Gamma \rho (E_m - E_H) \]  
(1)

Where \( p_H \) is Hugoniot pressure, \( E_H \) is Hugoniot specific energy, \( \Gamma \) is Grüneisen ratio.

\[ p = p_H \left(1 - \frac{\Gamma_0 \eta}{2}\right) + \Gamma_0 \rho_0 E_m \]  
(2)

Where \( \Gamma_0 \) is material properties, \( \rho_0 \) is reference density, Hugoniot curve fitting form is:

\[ p_H = \frac{\rho_0 c_0^2 \eta}{(1 - s \eta)^2} \]  
(3)

Where \( c_0 \) and \( s \) define the relationship between shock wave velocity \( U_s \) and particle velocity \( U_p \):

\[ U_s = c_0 + s U_p \]  
(4)

And then get the Mie-Grüneisen equation of state in Us-Up Hugoniot form:

\[ p = \frac{\rho_0 c_0^2 \eta}{(1 - s \eta)^2} \left(1 - \frac{\Gamma_0 \eta}{2}\right) + \Gamma_0 \rho_0 E_m \]  
(5)

Where \( \rho_0 c_0^2 \) is equivalent to elastic bulk modulus at small nominal strains.

Treating water as an incompressible and viscous fluid, the material properties of water can be defined:

| Table 1 Water medium material parameters |
|-----------------------------------------|
| \( \rho \) / kg \cdot m^{-1} | \( c_0 \) / m \cdot s^{-1} | \( s \) | \( \Gamma_0 \) | Viscosity / Pa.s |
| 1000 | 1450 | 0 | 0 | 0.001 |

3. Model validity verification

To verify the validity of the numerical method, the same calculation example as the experimental model in the literature\(^9\) is selected for simulation comparison. Verify that the model size is established in strict accordance with the test size 1:1, the water area size is 3.1m \( \times \) 3.3m \( \times \) 6m, the impact object is a solid cylinder with a diameter of 6mm and a length of 22mm, the material is No. 45 steel, with a mass of 4.88g and a water entry speed of 106.6m/s. The effectiveness of the CEL method is verified by comparing the velocity attenuation, intrusion displacement and cavitation shape at different times.

Figure 1 shows the comparison of the cavitation morphology obtained by experiment and simulation at different times. At 0.8ms, the cavitation completely wraps the impact object, and the splashing phenomenon of the liquid can be observed on the liquid surface; at 2ms, the cavitation begin to close, and the diameter reached the maximum; at 3ms, the back jet appeare at the tail of the cavitation; at 3.8ms, the cavitation bubble evolves into the sailing stage and separates from the free surface. From the process of cavitation generation, development, closure and collapse, it can be found that the cavitation shape obtained by simulation is in high consistency with the experiment, which preliminarily verifies the effectiveness of the CEL method.
3.

Figure 2(a) shows the comparison of the simulation and test velocity attenuation curves. At the initial stage of the impact, the huge instantaneous impact force causes the velocity to show a sharp attenuation phenomenon, which can be clearly observed from the velocity time history curve. At 4ms, the velocity obtained by the experiment attenuates to 49.76m/s, and the velocity obtained by the simulation attenuates to 48.23m/s, with a relative error of 3.07%, the experimental results and the simulation results are in good agreement. It can be seen from Figure 2(b) that at 4ms, the intrusion displacement obtained by the test is 282.45mm, and the intrusion displacement obtained by the simulation is 278.02mm, with a relative error of 1.57%. The numerical simulation results are close to the experimental results, which further proves the CEL method effectiveness.

4. Impact characteristic analysis and Structural strength assessment

In order to analyze the impact characteristics of the slender body in the process of water entry, based on the CEL method introduced above, the numerical simulation of slender body inclined into water at 15°, 20° and 30° was carried out. As shown in the figure 3, it is a schematic diagram of the calculation domain. The fluid area is 10m*5m*8m, the upper air is 3m high, and the lower part is water medium, free inflow and non-reflection boundary conditions are set around and at the bottom of the fluid area. The slender body length of 1m, diameter of 0.1m, the initial water entry speed is 150m/s, the material is No. 45 steel, and Johnson-Cook material model is adopted.

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**Fig.1 Comparison of cavitation evolution**

**Fig.2 Comparison of simulation results**

(a)velocity attenuation comparison  (b)Intrusion displacement comparison

**Fig.3 Computational domain model**
4.1. Impact characteristic analysis

Different from vertical entry, when the slender body tilts into the water, the head is initially disturbed by the impact load of asymmetric entry, in the process of tilting into the water, the coupling effect between the envelope state of the cavitation and the attitude deflection of the slender body is also involved. The acceleration, stress and strain curves of the head position of the slender body under different water entry angles are shown in Figures 4 and 5. The slender body forms a large impact load at the initial stage of water entry, and the acceleration, stress and strain all have a sharp change trend.

![Fig.4 Time-history curve of axial acceleration at different angles](image)

The peak acceleration value of entering water at 15° appears at 0.22ms, and the peak value reaches 1744.51m/s²; with 20° water entry angle, the peak appears at 0.19ms, the peak reaches 2014.72m/s²; with 30° water entry angle, the peak appears at 0.12ms, the peak reached 2014.72m/s². With the increase of the water entry angle, the acceleration peak value of the water entry impact increases significantly, and the peak time is slightly earlier, the impact load increases significantly. When the tail of the projectile touches the water, there will be an obvious disturbance.

![Fig.5 Time-history curve of stress and strain at different angles](image)

It can be seen from Figure 4(a) that the peak stress value of entering water at 15° appears at 0.22ms, and the peak stress reaches 257Mpa, the strain at this time reaches, with 20° water entry angle, the peak appears at 0.18ms, the peak reaches 336Mpa; with 30° water entry angle, the peak appears at 0.12ms, the peak reached 374Mpa. With the increase of the water entry angle, the stress generated by the impact increases significantly. The larger the angle, the higher the peak value, and the peak time is slightly earlier, but the stress value tends to be stable in general, and there is not much stress difference. Similarly, the strain increases slightly with the increase of the water entry angle, and the peak time is slightly earlier. It can be seen that the impact of the water entry angle on the impact load is very obvious. The impact load shows an upward trend with the increase of the angle. Appropriately reducing the water entry angle can help reduce the impact load.
4.2. Structural Strength Assessment

The impact load brings the high strain rate of the material, and the high strain rate loading has a significant impact on the plastic deformation and fracture of the material. During the plastic deformation of the material, the high strain rate brings different mechanical and thermodynamic problems from the static load, resulting in changes in the plastic deformation and fracture mechanism. At high strain rates, the dynamic yield limit is higher than the static yield limit. Therefore, in the plastic dynamics problem, the influence of the strain rate on the mechanical properties of the material should be considered.

The Johnson-Cook model is a viscoplastic constitutive model that can well describe the mechanical properties of metal materials. Its constitutive relation is:

\[ \sigma = (A + B \varepsilon^n)(1 + C \ln \dot{\varepsilon}^*) \]  

Where \( \sigma \) is equivalent yield stress, \( \varepsilon \) is equivalent plastic strain, \( \dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0 \) is strain rate, \( A \) is reference temperature, \( B \) is strain hardening factor, \( C \) is strain rate hardening factor, \( n \) is strain hardening index.

The above parameters can be fitted by querying the test data under the reference strain rate, then the constitutive model of the Johnson-Cook model at room temperature can be obtained as:

\[ \sigma = (502 + 35\varepsilon^{0.36})(1 + 0.002 \ln \dot{\varepsilon}^*) \]  

The residual strength of the slender body in the process of entering water is used as the standard for strength evaluation:

\[ P_\sigma = \frac{[\sigma] - \sigma}{[\sigma]} \]  

Where \( P_\sigma \) is residual strength coefficient of material, \([\sigma]\) is the allowable strength values of the material at different strain rates, \( \sigma \) is stress during material impact in water.

The analysis process is as follow. Obtain the strain rate time history response curve according to the obtained head position strain response time history curve, obtain the strength limit of the projectile material at different strain rates through the Taylor impact bar or Hopkinson test. Obtain the strain rate time history response curve according to the obtained head position strain response time history curve, fitting out the strain rate strength expression, then combined with the strain rate response time history curve, the strength limit value of the projectile head position at different times can be obtained, finally, the curve of residual strength factor changing with time is obtained by substituting residual strength formula. If the residual strength factor is positive, the structure is safe; if it is negative, the structure is unsafe.

Furthermore, Fig.5 shows the time-history curve of residual strength factor at different angles. When the slender body structure is inclined into the water at 15° and 20°, the residual strength factor of the structure is positive, the minimum residual strength coefficient at 15° is 0.4684, its far from the allowable intensity value; the minimum residual strength coefficient at 20° is 0.2732, which approaching the maximum allowable intensity value; the minimum residual strength coefficient at 30° reaches -0.203, the maximum allowable strength value is exceeded and the structure is unsafe. With the increase of the water entry angle, the residual strength coefficient gradually decreases, and the structure is prone to strength damage at an excessively large water entry angle.
5. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

1. The numerical simulation results of water entry impact based on CEL method are in good agreement with the experimental results, and can be used to study the high-speed water entry impact of slender bodies.

2. The water inlet angle is an important factor affecting the impact load. Under the same working conditions, the impact load and the water inlet angle show a positive correlation, the water impact load increases with the increase of the water inlet angle, and the peak time of the impact will be slightly advanced, appropriately reducing the water inlet angle will help to reduce the impact load.

3. Under the condition of 30° inlet angle, the minimum residual strength factor of the slender body structure in the process of water impact is less than 0; with 20° inlet angle, it is about 0.2732; with 15° inlet angle, it is about 0.4684. It shows that with the increase of the water entry angle, the residual strength factor gradually decreases, and the slender body is prone to strength failure when the water entry angle is too large.

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