Numerical investigation on water-entry impact load of TMA based on CEL algorithm

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Abstract. This work presents comprehensive numerical research on the impact load of the trans-medium aircraft (TMA) using the coupled Eulerian-Lagrangian (CEL) method during a water-entry event. The water-entry velocity, angle, and attitude play a significant role in the impact load characteristics of the water-entry trajectory. In this paper, a numerical model of a typical TMA structure is established to study the water-entry load with the velocity 0, 2m/s, 4m/s, 6m/s, 8m/s, the angle 90°, 80°, 70°, 60°, 50°, the attitude 90°, 80°, 70°, 60°, 50°. Subsequently, the variation laws of the impact load with different water-entry velocity, angle, and attitude are analyzed. The results obtained from this investigation can supply a good reference to structural design of the TMA.

1. Introduction
Trans-medium aircrafts (TMAs) have become a popular study topic because of their range of activities, unbalanced dominance in counteract, access to complex structures and relatively low cost. During the trans-medium maneuvering process, the motion of the TMA causes the stationary liquid to accelerate suddenly, inducing a tremendous force associated with momentum transfer. Most of the previous investigations on the water-entry physical process have focused on two aspects: the impact load and the dynamics of the cavity characteristics behind the body.

A simplified theoretical model by a numerical simulation FSI method for a single rigid wedge was performed by Carcaterra et al[1]. An experiment conducted measuring the velocity of the projectile after water entry and an empirical formula were carried out to study the water-entry phenomenon by Shi[2]. The hydrodynamic problem of twin wedges entering water vertically at constant speed was analyzed based on the velocity potential theory by Wu[3]. A review work undertaken in the field of water entry between 1929 and 2003 and future directions for research in the field of water entry were discussed by Seddon and Moatamedi[4]. Xu et al[5] investigated hydrodynamic problem of a two-dimensional asymmetrical wedge at constant speed based on velocity potential theory. A preconditioned Navier-Stokes (NS) method was developed for multiphase flow with application to the water entry problem of moving bodies by Nguyen[6-7]. Aiming at the lack research of high-speed water-entry for large projectile, Sun et al[8] studied the high-speed water-entry for hemispherical-nosed projectile in the method of fluid-solid coupling. The CFD approach was utilized to discuss the water entry and exit of axisymmetric bodies by Nair and Bhattacharyya[9]. An integrated experimental and theoretical framework to isolate the effects of oblique and asymmetric impact on the water entry of a rigid wedge was proposed by Russo et al[10]. Additionally, the violent water entry of spheres and inclined cylinders were described by Dyment[11] and Xia[12], respectively. Numerical study on the
cavity characteristics and impact loads of AUV water entry was formed by Shi[13-16]. Experimental study on the influence of the angle of attack on cavity evolution and surface load in the water entry of a cylinder was established by Sun[17]. Zheng et al[18] extended the CIP-based model for the treatment of water entry of two-dimensional structures with complex geometry.

In can be inferred that it is difficult to solve the impact load problem of the TMA during the water-entry process. In this paper, the CEL numerical method is adopted to investigate the impact load characteristics of a typical TMA structure. The accelerations of the TMA under different water-entry velocities, angles, and attitudes are analysed and discussed. The current paper is illustrated as follows: i) the theoretical description is given in Section 2, ii) Section 3 provides the numerical setup details, iii) the simulated results are discussed and reported in Section 4. Eventually, some conclusions obtained from the results are summarized in Section 5.

2. Theoretical description

2.1. Flow equations

The water is modelled by Euler approach, which considers the water as approximately incompressible viscous laminar flow. The volume response of the water medium is described by the $U_s-U_p$ format of the Mie-Grüneisen equation. The common form of Mie-Grüneisen state equation is given as:

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

where $p_H$ is Hugoniot pressure, $E_m$ is Hugoniot specific energy which merely relates with the density, $\Gamma=\Gamma_0\rho_0/\rho$, $\Gamma_0$ is the material parameter, $\rho_0$ is the reference density, $E_H=p_H\eta/2\rho_0$, $\eta=1-\rho_0/\rho$ is the nominal volumetric compressive strain. Further, we obtain:

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

The Hugoniot curve fitting relationship of common materials is:

$$p_H = \frac{\rho_0 c_s^2 \eta}{(1-s\eta)^2}$$ (3)

where the linear shock wave velocity $c_s$ is defined as:

$$c_s = c_0 + sU_p$$ (4)

The Hugoniot form of Mie-Grüneisen equation can be rewritten as:

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

Thus, we have described the volume strength and the hydrostatic volume response characteristics. Assuming that the shear response and the volume response are uncoupled, the viscous shear response is defined by Newtonian viscous shear model as:

$$S = 2 \mu \dot{\gamma}$$ (6)

2.2. Structural equations

The equation of motion for the structural part can be illustrated by the momentum balance equation as:

$$\rho_s \frac{\partial \mathbf{u}}{\partial t} = \nabla \cdot \mathbf{\sigma}_s - \rho_s (\nabla \mathbf{u}) \mathbf{u} + \rho_s f_b$$ (7)

where $\mathbf{u}$ is the structural velocity tensor, $\rho_s$ is the solid density, $\mathbf{\sigma}_s$ is the Cauchy stress tensor, and
\( f_b \) is the body force. Utilizing an iterative approach in a Lagrangian formulation, Eq. (7) can be expressed by:

\[
\rho \frac{\partial^2 d_b}{\partial t^2} = \nabla \cdot \left( \sum F^T \right) + \rho \dot{f}_b \tag{8}
\]

where \( F \) is the deformation gradient tensor. In the dynamic case, the strain energy and the kinetic energy of the body is provided by:

\[
E_s = \int_{\Omega} U dV \tag{9}
\]

\[
E_k = \frac{1}{2} \int_{\Omega} \rho \dot{u} u dV \tag{10}
\]

2.3. \textit{FSI solution algorithms}

In CEL algorithm, based on the immersed boundary method, the FSI is realized and solved by capturing the Euler-Lagrangian contact. Establishing the analysis function of the Lagrangian part movement in the Euler part, the Euler elements and the Lagrangian elements are correlated and coupled simulated.

3. Numerical setup

3.1. Geometry model presentation

A two-dimensional and a three-dimensional typical structures of TMA are adopted to investigate the water-entry characteristics. The geometrical sizes of the models are shown in Figure 1. For the two-dimensional model, the width is 45.826mm and the height is 30mm; for the three-dimensional model, the radius is 22.913mm and the height is also 30mm. Especially, the three-dimensional model is a shell type structure with the thickness of 3mm.

![Figure 1. Geometry models.](image)

The material of the solid structure is 7075-T6 aluminum alloy, and the corresponding material parameters are given in Table 1. The \( U_s-U_p \) model parameters of the water are shown in Table 2.

| Table 1. Material properties of 7075-T6 aluminum alloy. |
|---------------------------------------------------------|
| Parameter                  | Value        |
|----------------------------|--------------|
| Density                   | 2810 kg/m³  |
| Young’s modulus           | 72000 MPa    |
| Poisson’s ratio            | 0.33         |
| Yield stress               | 505 MPa      |
| Shear modulus             | 27068 MPa    |
### Table 2. $U_L-U_P$ model parameters of water.

| Variable | Value       |
|----------|-------------|
| $\rho$   | 1000 kg/m³ |
| $c_0$    | 1480 m/s   |
| $s$      | 0.267       |
| $\Gamma_0$ | 0.5       |
| $\mu$   | 0.001 Pa·s  |

3.2. **Definition of feature units**

In the study of the impact loads of TMA water-entry problem, it is necessary to evaluate the force characteristics using a physical variable. Therefore, the acceleration variable is adopted in the output results. Considering the computing cost, the solid structure is modelled as a rigid and the output point is located at the geometrical center. The unit of the acceleration variable is g, the value of which is 9.8 m/s².

3.3. **Computational domain and grid**

The simulation is carried out by the explicit finite element method based on a multi-medium coupling method. The water is simulated in the Eulerian formulation, whereas the motion of the TMA and the free surface are tracked using the Lagrangian formulation. The structure is modelled with Lagrangian elements and the water is meshed with Eulerian elements. The element size of the TMA structure is 1 mm, and the element size of the water field is 3 mm. The dimensions of the water field are 240 mm × 600 mm (2D case) and 240 mm × 240 mm × 600 mm (3D case). The computational domain and the meshing of the simulation numerical finite element model is displayed in Figure 2. The VTF tool is used to defined initial water field. Since the large simulating cost, the computing codes were run on a cluster with one management node and five computing nodes and every node has 112 cores and 512 GB RAM, i.e. 560 cores were used in this work.

![Figure 2. Computational domain an meshing.](image)

3.4. **Simulation conditions**

The boundary conditions are set as $V = 0$ and the gravity effect is considered. In order to research the maximum acceleration loads during the water-entry process under different water-entry velocities, water-entry angles, and water-entry attitudes, 125 cases of 2D model and 5 cases of 3D model are simulated. The water-entry velocity $V$, the water-entry angle $\alpha$ and the water-entry attitude $\beta$ are defined as Figure 3. The simulation time is set as 0.5 s and the nonlinear geometrical deformation is included in the computing process. The cases of $V$, $\alpha$, and $\beta$ are illustrated in Table 3.
Figure 3. Definitions of water-entry variables.

Table 3. Values of water-entry variables.

| Water-entry velocity $V$ | Water-entry angle $\alpha$ | Water-entry attitude $\beta$ |
|--------------------------|-----------------------------|-----------------------------|
| 0 m/s                    | 90°                         | 90°                         |
| 2 m/s                    | 80°                         | 80°                         |
| 4 m/s                    | 70°                         | 70°                         |
| 6 m/s                    | 60°                         | 60°                         |
| 8 m/s                    | 50°                         | 50°                         |

4. Results and discussions

The maximum impact acceleration (MIA) performances under different water-entry velocities, water-entry angles and water-entry attitudes are analyzed and discussed in this section. The results of the 125 2D-model cases and the 5 3D-model cases are characterized. The water-entry velocity $V$ varies from 0 m/s to 8 m/s, meanwhile the water-entry angle $\alpha$ and water-entry attitude $\beta$ vary from 90° to 50°.

4.1. Effect of water-entry velocity

The MIA of the 2D model varies with the water-entry velocity $V$ under different water-entry angles and water-entry attitudes are given in Figure 4 and Figure 5, separately. The results of the MIA for the 3D model, which relate with the water-entry velocity $V$ at the water-entry angle of 90° and the water-entry attitude of 90°, are display in Figure 6. From the results, we can obtain that the MIA increases with increasing water-entry velocity and has a linear relationship with the square of the water-entry velocity in the near term. The MIA is in the range of 30g at 0 m/s and 180g at 8 m/s.

Figure 4. MIA versus water-entry velocity under different water-entry angles of 2D model.
4.2. Effect of water-entry angle

The MIA of the 2D model varies with the water-entry angle $\alpha$ under different water-entry velocities and water-entry attitudes are given in Figure 7 and Figure 8, separately. As is seen from Figure 7 and Figure 8, the MIA decreases first and increases as the water-entry angle increases for $\beta=50^\circ$ and $\beta=90^\circ$. For the cases of $V=2$m/s and $V=8$m/s, there are no obvious trends or patterns for relationship between the MIA and the water-entry angle and some fluctuations of the MIA occur.
Figure 7. MIA versus water-entry angle under different water-entry velocities of 2D model.

Figure 8. MIA versus water-entry angle under different water-entry attitudes of 2D model.

4.3. Effect of water-entry attitude
The MIA of the 2D model varies with the water-entry attitude $\beta$ under different water-entry angles and water-entry velocities are shown in Figure 9 and Figure 10, separately. It can be concluded from Figure 9 and Figure 10 that the MIA has the same trend as previous results. The most cases, the MIA first increases, then decreases, and then increases again. In summary, the MIA has an obvious relationship with the water-entry velocity, and there are no obvious law with the water-entry angle and the water-entry attitude.
5. Conclusions
The CEL-based numerical model is extended to simulate the water-entry impact loads of the TMA for two-dimensional and three-dimensional structures. First of all, the theoretical details are supplied. Then the numerical model is modelled for the water-entry process of the TMA structures and more than 125 cases are carried out. Finally, these numerical investigations perform evidence for the influence of the water-entry velocity, the water-entry angle, and the water-entry attitude on the MIA, which can help us to understand and evaluate the MIA of the typical TMA structures and predict the structural strength furtherly.

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