Numerical Simulation of Wave Landing Loads Characteristics of Twin-Foot Seaplane

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Abstract. The coupled Euler-Lagrangian method is used to simulate the load characteristics of a Twin-Foot seaplane when it is landing in waves. The fluid domain is described by Euler, the structure is described by Lagrangian, and the coupling interaction between the Euler material and the Lagrangian element is simulated by the enhanced immersion boundary method. Firstly, a three-dimensional numerical wave tank is established, and the accuracy of numerical wave-making is verified by linear wave theory. Then, the numerical calculation of seaplane wave landing load at different wave heights with the same wave length is carried out, Lastly the numerical results compared with the model experiment of towing tank. The numerical simulation results are in good agreement with the model experiment results. The results show that there will be obvious bouncing phenomena when the seaplane landed in the wave, and the higher the wave height is, the greater the load will be generated when the wave length is the same.

1. Introduction

With its advantages of large loading capacity, wide flight range and ultra-low altitude aircraft, seaplane has incomparable advantages over roadbed aircraft in search and rescue at sea, monitoring and protection of marine environment, protection of marine rights and interests, and low altitude flight experience. The landing of a seaplane in the ocean environment is the most important working condition during its mission. The impact process of landing on the water surface is short and the load is large. The impact load is the most important problem affecting the safety of the seaplane. Especially in the sea area where the wave height is relatively high, the landing load of the aircraft is very large. Therefore, it is of great significance to study the wave landing loads of seaplane [1].

In recent years, domestic and foreign scholars have carried out some research work on the dynamic response of seaplane, amphibious aircraft and civil aircraft under water in calm water. Luo [2] used ALE coupling algorithm to analyze the influence of attitude angle and sinking speed on load characteristics of amphibious aircraft in calm water. Ma [3] established a numerical regular wave model based on linear wave theory, and studied the dynamic response of amphibious aircraft landing in water at different sinking velocities with different wave strike positions. Chu [4] studied the landing load of ground effect aircraft in calm water surface by theoretical and experimental means. Sun[5] used Dytran general coupling algorithm to simulate the surface landing of amphibious aircraft in calm water, and compared it with the model test results to verify the correctness of the simulation calculation. Yao[6] analyzed the dynamic characteristics of amphibious aircraft landing on water
based on CEL algorithm, and compared the dynamic response of aircraft structure under different attitude angles and vertical velocities. Wang [7] simulated the evolution and development of water-entry voids of spheres based on ABAQUS explicit CEL method, and compared it with ballistic data of water-entry experiments, which showed the effectiveness of CEL method in solving fluid-solid coupling interaction.

In summary, the horizontal velocity, sinking velocity and attitude are the most important factors affecting the landing load of seaplane and amphibious aircraft. Some scholars have studied the landing loads and motion responses of amphibious aircraft at different wave encounters, but they have not been compared with the experiments.

In this paper, the ABAQUS explicit dynamic solver Explicit is used to establish a three-dimensional fluid-structure interaction coupling model using CEL algorithm. Firstly, the pusher wave-making method is used to simulate the wave model, and the accuracy of the numerical wave is verified by the wave height recognition technology. Then, the landing cases of the seaplane numerical model with different wave heights with the same wave length are calculated. The curve of the vertical displacement and the vertical velocity changing with time in the process of landing is obtained. Compared with the simulation results, the motion response and load characteristics under different wave heights are analyzed.

2. Numerical Method

2.1. CEL Method

CEL is usually called coupled Eulerian-Lagrangian method, which can simulate the coupling interaction between Eulerian materials and Lagrangian elements. The Euler-Lagrangian contact formula is based on the enhanced immersion boundary method. In this method, the Lagrangian structure occupies the empty area in the Euler mesh. The contact algorithm automatically calculates and traces the interface between the Lagrangian structure and the Euler material. The remarkable advantage of this method is that it does not need to generate a coordinated grid for Euler domain. A simple and regular Euler element usually produces better accuracy.

CEL is based on the fluid volume method in simulating hydrodynamic implementation. When material flows through the grid, it traces material by calculating its Euler volume fraction in each element. By definition: if a material is fully filled with a unit, its volume fraction is 1.0; if there is no material in a unit, its volume fraction is 0. In this paper, the method is fully utilized to track the volume fraction of the element near the free surface, and a wave elevation recognition technology based on CEL is developed. The accuracy of numerical wave generation is verified by this technology.

2.2. Fluid Model

The CEL in Explicit, an ABAQUS dynamic solver, approximates incompressible viscous laminar flow of water controlled by N-S equation using Mie-Grüneisen equation of state in linear form [8].

The volume response of water is described by Mie-Grüneisen equation. Its most commonly used form is:

\[ p = K \varepsilon_{vol} \]  \hspace{1cm} (1)

Where \( K \) is the bulk modulus of the material. The linear equation is as follows:

\[ p = \frac{\rho_0 c_0^2 \eta}{(1 - s \eta)^2} (1 - \frac{\Gamma_0 \eta}{2}) + \rho_0 \rho_s E_s \]  \hspace{1cm} (2)

Where \( c_0 \) and \( s \) is the two parameters of the linear shock wave, \( U_s = c_0 + s U_p \), \( U_s \) is the wave velocity and \( U_p \) is the particle velocity. \( \eta = 1 - \rho_0 / \rho \) is equal to the nominal volume compression strain \( \varepsilon_{vol} \). If \( s = 0 \) and \( \Gamma_0 = 0 \) is defined, the volume response is equal to the bulk modulus. Tab. 1 shows the material properties of water.
Table 1. Material Properties of Water

| Parameter | Value       |
|-----------|-------------|
| ρ         | 1000 kg/m³ |
| γ         | 0.0089 Ns/m² |
| c₀        | 1450 m/s   |
| s         | 0           |
| Γ₀        | 0           |

3. Numerical Model

3.1. Structure and Fluid Model

Two-dimensional view of a Twin-Floater seaplane is shown in Fig 1 [9].

Figure 1. Two-dimensional view of a Twin-Floater seaplane

In order to reduce the calculation cost and shorten the calculation time, it is simplified to floating wave landing. According to the calculation of wing aerodynamic lift, the lift, drag and pitch moments at the center of gravity at the initial horizontal velocity and attitude angle are obtained, and the aerodynamic loads are treated equivalently in the process of landing numerical simulation. In the numerical simulation of landing, the concentrated load curve of reference point is defined, and the equivalent aerodynamic force is applied to the centre of gravity of the seaplane. The validity of this aerodynamic equivalent loading has been verified by numerical calculation [3].

The Twin-Floater is defined as a rigid body by reference point, and a 1/2 float model is adopted. The float structure adopts Lagrangian shell element S4R and Euler element EC3D8R for water fluid. The geometric model is shown in Fig 2. The size of float mesh is 10 mm and the number of units is 7761. The minimum mesh size of the water is 10 mm and the number of elements is 1936550. The density of float is 2100 kg/m³, the modulus of elasticity is 69 Gpa and Poisson's ratio is 0.33.

Figure 2. Water landing of seaplane geometric model

3.2. Fluid-Structure coupling Model
According to the actual parameters of the Twin-Float seaplane [9], the mass and pitching inertia of the reference point are set. Symmetrical boundary conditions are defined on the symmetrical surfaces of fluid and float, and Euler non-reflective boundary conditions are defined on other boundary surfaces of fluid. The reference point of the buoy is constrained, and only the displacement in X and Z directions and rotation around Y axis are allowed. The vertical displacement and vertical velocity of the reference point are recorded with time. The volume fraction tool of CEL is used to calculate the percentage of material in the water near the free surface aiming at verifying the wave accuracy.

4. Numerical Wave Tank

4.1. Push-plate Wave-Making Theory

The numerical push-plate wave-making is the basis of studying the interaction between structures and waves. The initial position of the push plate is \( S/2 \), \( \omega \) is the push frequency. Based on linear shallow water theory, the relationship between motion range of push plate and wave height is given [10, 11]:

\[
H = \frac{2(\cosh(2k_p h) - 1)}{\sinh(2k_p h) + 2k_p h}
\]

(3)

Where \( k_p \) is wave number, \( h \) is water depth and \( H \) is wave height.

4.2. Wave Elevation Recognition Technology

Based on the volume fraction of Euler material, the material volume percentage of Euler element at free liquid level is recorded, and the material percentage of all Euler elements near free liquid level is added up. By arranging the numerical wave altimeter on the free surface with Euler element, but the Euler element on the free surface must cover the maximum wave height range, as shown in Fig 3.

![Figure 3. Layout of Wave Altimeter](image)

4.3. Regular Wave Simulation

If the depth \( H \) of water is 0.5m, the movement period \( T \) is 1.3724s and the push distance \( S \) is 33.168mm. The theoretical wave height is obtained from the above formula (3), and wave height is 0.4m, the wave number is 2.5133, the wave length is 2.5m. Because value of wave height, depth and steepness, it can be judged that the wave belongs to weak non-linear wave with finite water depth. A numerical wave elevation monitor is set up at 2.5m and 7.5m behind the push board. Fig. 4 shows the wave elevation time-history curves at 2.5m and 7.5m. From the graph, it can be seen that the numerical wave-making technology based on CEL meets the requirement of wave landing of seaplane.
5. Model Experiment
According to Furude similarity criterion, the model of Twin-Float seaplane is designed. The seaplane is suspended on the motion control system by wire rope, and the initial attitude angle and roll angle are adjusted by front, back, left and right support rods, just because of this the model can kept stable during the acceleration process. After the model is installed, the initial height of the model from the water surface is debugged through the vertical motion mechanism. During the test, the trailer is started, the model is accelerated to a certain horizontal speed, and then the wire rope is disconnected by using the electromagnetic throwing device to make the model impact freely on the wave surface. The model landing wave experiment of a Twin-Float seaplane is shown in Fig. 5.

![Wave Elevation Time-History Curves at Positions x=2.5m and x=7.5m](image)

**Figure 4.** Wave Elevation Time-History Curves at Positions x=2.5m and x=7.5m

![Wave landing test model of Twin-Float seaplane](image)

**Figure 5.** Wave landing test model of Twin-Float seaplane

6. Results and Discussion

6.1. Calculation Cases
In order to study the effect of wave height on impact loads, the parameters in Tab. 2 are the same except wave height. Horizontal velocity corresponds to stall velocity when the surface of the real aircraft glides down 0.88g under overload, and vertical velocity corresponds to the sinking velocity of the real aircraft 1.0m/s. Height wave ratio is less than 1/20, which accords with the theory of wavelet wave under linear assumption. The bottom step of the float is sliding surface, and the broken step is near the centre of gravity. Therefore, it is safer for the seaplane to occur the step and impact water than for the bow and stern of the float then the attitude of the seaplane is 5~7 degree. So the initial attitude of seaplane is 6 degree in this paper.
Table 2. Initial state of wave landing of seaplane

| cases | Wave Height/m | Wave Length/m | Attitude /Degree | Horizontal velocity/m/s | Vertical velocity/m/s |
|-------|---------------|---------------|------------------|-------------------------|---------------------|
| 1     | 0.04          | 5.0           | 6                | 15.19                   | 0.236               |
| 2     | 0.06          |               |                  |                         |                     |
| 3     | 0.08          | 5.0           | 6                | 15.19                   | 0.236               |
| 4     | 0.10          |               |                  |                         |                     |

6.2. Motion characteristics
According to the velocity and displacement curves of reference points, the landing motion characteristics of seaplane under different wave heights are analyzed. Velocity and displacement curves reflect the motion characteristics of the aircraft in underwater waves. As shown in Fig. 5-6, the higher the wave height, the greater the response of landing motion. After the float encounters waves for the first time, it bounces, reaches the maximum vertical displacement, glides for a certain distance under the action of aerodynamic lift and gravity, and then encounters waves for the second time. Obviously, the motion response of the first encounter wave is larger than that of the second encounter wave. During the second encounter wave, the motion response of different wave heights is not much different.

Fig. 6 also shows that the higher the wave height, the larger the bouncing motion of the float after the first wave encounter, but the later the second wave impact.

![Figure 6. Vertical displacement and velocity curves of seaplane at different wave heights](image)

6.3. Load characteristics
The displacement curve can be double differentiated to obtain the vertical acceleration curve of the seaplane with time, as shown in Fig. 7. The figure also shows the landing experiment results of a Twin-Float seaplane model with a wave height of 40mm and a wave length of 5 m. Through comparative analysis, the vertical acceleration curve obtained by numerical simulation is in good agreement with the data collected by the acceleration sensor of the model experiment. It can be seen in Fig. 7 that the first wave landing process of the seaplane model has been completed in about 0.15 seconds. So the water process is a dynamic process of instantaneous impact. During the landing experiment of seaplane, the impact point between the model and the wave surface has a high randomness. When numerical simulation is carried out, the initial state of the model is just in contact with the water surface and hull baseline close to the wave surface. So the acceleration by the landing of the numerical simulation increases rapidly. In the wave landing experiment, the seaplane does not necessarily impact the wave surface when it touches the water. So the acceleration growth rate by model experiment is slower than that in numerical simulation.
7. Conclusions
In this paper, the CEL method in ABAQUS/Explicit solver is used to simulate the push-plate wave-making and the interaction between float and water. The accuracy of numerical wave-making is validated by the wave elevation recognition technique developed by free surface volume fraction. The model experiment results are compared with the simulation results of wave landing, which verifies the accuracy of the simulation results of wave landing.

The landing results of the seaplane at different wave heights and the same wave length are analyzed. The seaplane's wave landing causes obvious bouncing phenomena, and the higher the wave height, the greater the motion response. Generally speaking, the motion response of the first encounter wave is larger than that of the second encounter wave, and the higher the wave height, the later the second encounter wave is.

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