Numerical Simulation of Seaplane Water Takeoff Process Based on CFD

Xiaolong Zheng*, Shineng Quan, Bin Wu, Xiaohong Han

China Special Vehicle Research Institute, Key Aviation Scientific and Technological Laboratory of High-Speed Hydrodynamic, Jing Men, China

*Corresponding author e-mail: zhengxiaolong1001@126.com

Abstract. In order to reduce the development cost of seaplane and shorten the research cycle, a numerical method to simulate seaplane take-off process is proposed. Taking the model of a seaplane as an example, carrying out the numerical simulation of seaplane taxing on surface of calm water at different speeds, and compare the calculation values with the experimental results. The comparison shows that the taxing performance obtained by simulation is well match for the experimental flow behaviour, and the error between experimental data and numerical calculation values is very small, which indicates that it is feasible to use this CFD method chose in the paper to simulate a seaplane taxing and taking off from the clam water.

1. Introduction
Take-off and landing are the key stages of a plane, it is necesary to study the calculation method of takeoff and landing performance for overall design and flight safety verification of aircraft. As the seaplane, taking off from the clam water is the most critical procedure of the complete design process. Lots of parameters will affect the hydrodynamic characteristics of a seaplane when it glides over the surface of clam water, which will put the aircraft into many dangerous maneuvers such as "dolphin movement", "bow trim" and so on. Until then, mostly research about hydrodynamic performance of seaplane mainly by experiment[1,2,3,4], due to the high cost and long development cycle, some research cannot be carried out. However, with the great improvement of computer and the technology of commercial software, it is possible to construct a numerical tank to predict the hydrodynamic performance of seaplane.

In the last few years, lots of experts and scholars have pay attention to the numerical simulation research on the water landing of seaplane[5, 6], there also a small number of scholars have concerned about the feasibility of theoretical analysis in the field of seaplane takeoff[7], but less research has been carried out on the rapidity performance of seaplane during the water takeoff process. In this paper, a numerical prediction method based on STARCCM+ will be chose, the overlapping grid method will be used to realize the six degree of freedom motion of seaplane in CFD software, it will simulate the plane taxing on the surface of clam water at different speeds. The calculation results are compared with it obtained by the experiment, the feasibility of choose CFD software to simulate the takeoff process of seaplane on surface of calm water is verified.

2. Controlling equations
The numerical prediction of seaplane take-off performance is carried out in a viscous numerical tank, which is established in commercial software.
Based on the incompressibility of the fluid, the controlling equations including continuity equation and the RANS equation are as follows:

\[ \frac{\partial \rho}{\partial t} = 0 \]  

\[ \rho \frac{\partial \vec{u}}{\partial t} + \rho \frac{\partial \tau}{\partial x_j} = \rho \vec{F} - \frac{\partial P}{\partial x_j} + \mu \left( \frac{\partial \vec{u}}{\partial x_j} - \frac{\rho u_j u_j}{\rho} \right) \]  

In the above equations, \( \vec{u} \) represents time-averaged speed, \( u'_i \) represents fluctuating speed, \( \rho u'_i \) represents RSM.

3. Computational model and boundary condition

3.1. Computational model

In the process of high-speed taxing on the water of the seaplane, lift force is mainly provided by the hull structure and the wing. In order to save the computing resources, the model selected for numerical calculation is the hull structure of seaplane, it does not include wings, tail and other accessories. Applying a aerodynamic unloading vertically upward at the center of gravity to simulate the aerodynamic lift of wings.

The length of the seaplane model is 3.754m which abbreviated as \( L \), and the angle of the seaplane floating on the water is 2.708°. Considering that the hull structure of seaplane will have a large trim and heave at high speed, the calculation may diverge due to the large translation and rotation, so this paper will take the overlapping grid to calculate the water taxing of the single hull model. A small grid domain is established to surround the hull which is called small domain, only this small domain has 6-DOF motions during the calculation. The calculation model and small domain are an integral part. When the model taxis on the surface of clam water and moves with 6-DOF motion, only the small domain can lift and rotate, and the large domain of the flow field will be no movement. The data between the small domain and the large domain of the flow field is transmitted through overlapping domain interpolation.

The motion relation of two computational domains is shown in Figure 2. The small domain always moves with the hull together, and the large domain is always in a static state without any displacement. The calculation tank of seaplane taxiing and taking off from the water surface is composed of flow field and overlapping zone. In order to capture the flow behaviors more accurately, the \( Y + \) of the grid is controlled below 100, and the number of fluid mesh is 4.65 million.
3.2. Boundary condition

The momentum equation is dispersed by implicit finite volume method, and solved in time domain by separating solver. The free surface of water is captured with VOF method, and the gravity effect is taken into account.

The outlet boundary is set as pressure-outlet while the other boundaries are all set as velocity-inlet. Turbulence model is k-w SST. Chose the second order upwind model to enhance the accuracy, the time step $\Delta T = L / 200V$. The hull model is set as no slip wall boundary, but all the other surfaces of tank are set as slip wall.

4. Computational values and experimental results

4.1. Computational values and experimental results

There are four stages during the seaplane taxing and taking off from the surface of water, they were the hull borne stage, transitory stage, taxi stage and takeoff stage. Because of the seaplane model only contains a single hull, so this simulation will mainly carried out for the first three stages.

Table 1 shows the computational values and experimental results of the seaplane while taxing on clam water at different speeds. The resistance performance is expressed by the coefficient $R/G$, it is the ratio of the model resistance to its own gravity.

| Speed (m/s) | Experimental results | Calculation results |
|------------|----------------------|---------------------|
| R/G        | $\theta$ (°)        | $\delta$ (mm)        | R/G        | $\theta$ (°)        | $\delta$ (mm)        | Error (%) | Error (%) |
| 2          | 0.043                | 3.08                | -4.01     | 0.042                | 2.92                | -5.19     | -3.7      | -8.44 |
| 4          | 0.121                | 4.87                | 7.48      | 0.115                | 5.01                | 2.7       | 6.4       | -16.94 |
| 6          | 0.121                | 5.80                | 32.52     | 0.123                | 6.15                | 5.72      | 35.4      | 8.13  |
| 8          | 0.159                | 8.55                | 98.09     | 0.153                | 8.92                | 4.18      | 102.3     | 4.12  |
| 10         | 0.123                | 7.33                | 110.58    | 0.116                | 7.31                | -0.25     | 118.8     | 6.92  |
| 11         | 0.101                | 6.37                | 111.86    | 0.093                | 6.29                | -1.27     | 120.6     | 7.25  |
| 12         | 0.094                | 6.25                | 114.82    | 0.085                | 6.17                | -1.33     | 125.1     | 8.22  |

As it shown in the table1, the data of three main parameters calculated by CFD are in good agreement with it of experiment, this prove that this CFD method used in this paper can accurately predict the taxing and takeoff performance of seaplane on clam water.

The resistance coefficient curve usually has a peak during the transitory stage, for this plane, the speed of resistance peak is 8m/s. Comparing with the experiment results, it can be found that the calculated results are in a high accuracy, especially for the speed below 10m/s. The trim angle and heave can be simulated very accurately at every speed, but the resistance values are usually lower than the experimental ones when the speed above 8m/s, the maximum error of $R/G$ reached 9.34% at 12m/s. This is caused by the fact that the splashing resistance of the seaplane at high speed is relatively large, but the traditional CFD method is difficult to simulate the tiny surface elements in the splashing fluid.

![Figure 2. Relationship between model displacement and mesh](image-url)
4.2. Wave height of free surface

Figure 3 shows the wave height cloud chart at different speeds. When the seaplane gliding on the surface of clam water, the trim angle will increase gradually with the speed and reach a stable angle, while the heave will increase gradually with the speed until the plane leaves the surface of water. This will cause the after body of plane to leave the water first at a high speed. With the increase of speed, the aerodynamic lift force provided by the wings gradually pushes the front body out of the water surface.

Figure 4 shows the wave height cloud chart at 8m/s. Comparing it with figure3(d), the location of main splash is basically the same, but the splash range in figure3 is smaller than it in figure4. This is because the scope of splash is large, and the grids used in CFD calculation cannot be refined in the whole tank, which will greatly increase the amount of calculation. Therefore, it is difficult to accurately capture the splash in the area far away from the hull, which leads to the calculation value of resistance is smaller than it of experiment at high speeds.

Figure 4. Free surface at 8m/s
4.3. Phases distribution

Figure 5 shows the phases distribution cloud chart of hull bottom at different speeds, it shows the whole process of a seaplane taxiing and taking off from the water. At low speed, the hull is in the stage of drainage navigation, and the phases distribution of hull bottom is not mixed with air. As the speed gradually increases, the hull step begin to block the flow of water and form an air-pocket area. With the gradual increase of the speed, the trim angle and heave of the model also increase, which leads to the gradual decrease of the water receiving area of the forebody, and the water receiving area gradually moves backward until the afterbody is completely out of the water. When the speed is about to reach the speed of $V_{gw}$, the hull is basically taxiing on the water by forebody. When the speed reaches $V_{gw}$, the lift of the wings and the hydrodynamic lift of the hull will make seaplane take off from the water.
Heave of the seaplane usually increases with the increasing speed. In general, the increase rate of heave began to reduce when the velocity reaches 70% $V_{gw}$, the hull basically maintain at a same height. But the trim angle will gradually decrease after the hull passes the resistance peak, which will lead to the afterbody slowly lifting up to the water surface. In the state of high speed, the seaplane glide on the water only on the forebody, and with the further increase of the speed, the lift force will make the fuselage all out of the water, and then it will take off from the surface of water at last. Figure 6 shows the phases distribution of the middle longitudinal section of the hull, it basically embodies the three key processes of the seaplane take off from calm water surface.

5. Conclusion

In the paper, CFD method is chose to simulate the takeoff process of a seaplane, the principle of seaplane taking off from the water is analyzed. The CFD method proposed in this paper to simulate a seaplane taxing and taking off from the clam water is feasible. This method can accurately predict the hydrodynamic performance parameters of the seaplane when taking off on the surface of clam water, which will obvious increase the efficiency of linear optimization in the initial design stage of seaplane, it will provide a reliable input for the model experiment, and it also can shorten the development cycle of the seaplane to a great extent. In the meantime, this method will provide technical support for the performance prediction of seaplane taking off from rough water surface.

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