Investigation of Blocking Effect of Aviation High-Speed Towing Tank Based on CFD and EFD

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Abstract. Taking the unpowered model of a seaplane as the object, the blocking effect of aviation high-speed tank was studied by experimental and numerical methods in this paper. Firstly, the experiment of air field and drag were carried out in the bottom and front of the trailer. The experimental results of air field showed that the blocking effect of the air field was obvious in the bottom of trailer, while ignored in the front of trailer. The results of drag experiment under two conditions showed significant difference at mid-high speed, which proved the influence of blocking effect was obvious. RANS method and overset grid were adopted in numerical simulation, and the accuracy of numerical method adopted in this paper was verified by comparing computed results of the model in the bottom of trailer with the experimental results. The computed results of hydrodynamic performance of the seaplane in finite and infinite domain showed that the influence of the blocking effect of water could be nearly ignored, but the influence of the blocking effect of air field was dominated. Finally, the hydrodynamic performance of the seaplane under the trailers with different sizes of chassis were carried out. The computed results showed that within the certain range, the degree of blocking effect of air field increased with the increase of geometrical variables of trailer chassis, further, which reached the maximum and kept constant when the variables exceeded a certain value.

Keywords: Seaplane; Hydrodynamic performance; RANS; Overset mesh; Blocking effect

1. Introduction

The boundary effect is inevitable in any towing test due to the limited boundary. There are three kinds of boundary effect, containing blocking effect, shallow water effect and wall effect. Generally speaking, for the ship test in towing tank, blocking effect is the largest one while the shallow water effect and wall effect can be ignored[1-3]. The wind speed has a small effect on the test of low-speed ship surface ship, but the change of wind speed has a greater impact on hydrodynamic results of high-speed vehicles such as seaplane, ground-effect aircraft and planing boat. Ideally, the wind speed at the bottom of the high-speed trailer was equal to the speed of the trailer for the aviation high-speed towing tank. However, when the high-speed trailer travels fast in the tank, the wind speed in the bottom of the high-speed trailer will increase because of the blocking effect caused by the limited air flow along the trailer chassis, tank wall and water surface. To reduce the impact of increment of wind speed in the bottom of high-speed trailers, some high-speed tanks, such as the one at Russia's central institute of air

IOP Conf. Series: Materials Science and Engineering 692 (2019) 012040 doi:10.1088/1757-899X/692/1/012040

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and fluid dynamics, placed the models in the front of trailer. Therefore, it is necessary to consider the blocking effect of both water and air fields when study the blocking effect in aviation high-speed towing tanker. At present, there were many researches on the blocking effect of tank test focusing on the medium and low speed ship instead of high-speed vehicle. A modified formula of blocking effect was given in the 13th international towing tank conference (ITTC)[4]. Sheng Zhenbang pointed out that the shallow water effect and wall effect of ship model test in towing tank could be generally ignored while blocking effect was the main part of boundary effect[5]. Comparing the modified formulas of blocking effects in the drag test of ten ship models in three tanks with differente sections, Xie Kezhen pointed out that the influence of the tank width on the drag was greater than that the tank depth and the influence of the width-depth ratio should be considered when selecting the modified formula[6]. Studying the influence of different widths and depths of tank on the attitude of KVLCC2 ship model, Evert Lataire proposed the equivalent width mathematical model for solving the attitude change of ship model[7].

The unpowered model of seaplane was adopted in this paper to study the blocking effect of aviation high-speed towing tank by experimental and numerical methods. The air field and drag test in the bottom and front areas of the trailer were carried out. The numerical simulation was mainly including two parts. On the one hand, the hydrodynamic performance of the seaplane in the finite and infinite domain was computed to study the blocking effect of water and air field. On the other hand, the hydrodynamic performance of the seaplane in the bottom of the trailers with different sizes of chassis to study the influence of trailer chassis geometry parameters on blocking effect.

2. Geometry and Gird

2.1 Geometry

The unpowered model of seaplane was taken as the object of the experiment and numerical simulation. The angles of flaps and elevators in this model was 0 degree, and the buoy was above the water surface during the whole test. The geometrical model of seaplane was shown in figure 1. All experiments were carried on aviation high-speed towing tank with the size of 510m×6.5m×6.8m as figure 2 shown. The size of high-speed trailer is 9.6m×6.5m×2.5m, which is 2.1m above the water surface. The accuracy of speed is between 0.1% and 0.3% in aviation high-speed towing tank.

![Figure 1. Geometrical model of seaplane.](image)

![Figure 2. Aviation high-speed towing tank.](image)

2.2. Grid generation and boundary condition

The trimmed mesh adopted in this paper was generated the high quality grid for complex surface of seaplane, and the refined mesh density was achieved by using volumetric controls applied to the area with serious flow separation and near-wall surface. The overset mesh was used to solve the problem of model motion. The grid distributions of finite domain and infinite domain were shown in figure 3 and figure 4. The mesh distributions of the seaplane in the front and bottom of the trailer were same except the difference of the model position. Since the model and trailer were geometrically symmetric, the half model was adopted in all simulation. The boundary condition of model and trailer surface was set as no-slip wall. As shown in figure 5 and 6, velocity-inlet boundary condition was imposed on the
inlet, top, side and bottom, and the boundary conditions of outlet was set as pressure-outlet in the infinite domain. While the condition of side and bottom were set as wall in the infinite domain where the influence of side wall and bottom should be considered. The size of finite domain was set according to the actual tank, and the size of infinite domain were set as follow: 

\[-5.0L \leq x \leq 1.5L\ ,\ 0L \leq y \leq 2.5L\ ,\ -2.0L \leq z \leq 2.0L.\]

Referring to previous work and literature [8], RANS method and SST K-\(\omega\) turbulence model were adopted for simulation in this study. The governing equation was discretized by the second order upwind finite volume method (FVM). The convection term was discretized by the second order upwind scheme, and the diffusion term was discretized by the second order scheme. Free surface was captured by two-phase fluid volume (VOF) technology.

3. Experimental methods

3.1. the design of air field experiment

To research the variation of air field around the trailer, wind speed measurements were installed in the front and bottom of the trailer separately. The five-hole pitot tube, five micro-pressure sensors with amplification and temperature compensation and a data acquisition system were installed in the bottom of trailer. The five-hole point tube had been calibrated in the wind tunnel of the Fluid Mechanics Laboratory, and the computer data acquisition software can display and record the wind speed in real time. Due to the installation problem of the five-hole pitot tube, the wind field of the front of trailer were tested by the ultrasonic anemometer. The measuring points were arranged around the seaplane, and the positions of the test points were as shown in figure 7, and the layout of ultrasonic anemometer was shown in figure 8.

3.2. the design of resistant experiment

The experiment in the bottom of the trailer was conventional, while it was the first time to carry out the model test in the front of the trailer for the hydrodynamic research center, so only the experimental
device of the latter was described here. The experiment device mainly included trailer, forward extension device, movement device and restrainer. The forward extension device was consolidated with the trailer for extending the position of the test model to the front of the trailer. The movement device guaranteed the degree of freedom of the model, including a small pulley, a lifting rod and Barycentric connecting rod. During the test, the lifting rod was vertically translated with the model. To ensure that the model can rise and fall freely, the lower end of the Barycentric connecting rod was articulated with the model at the center position. The restrainer mainly limited the yaw motion of the model. The front device of trailer was shown in figure 9.

![Figure 7. Location of measuring points.](image)

![Figure 8. The layout of ultrasonic anemometer.](image)

![Figure 9. The typical layout of device in the front of trailer.](image)

![Figure 10. The experimental results of measuring points.](image)

4. Results and Discussion

4.1. wind speed measuring experimental results analysis
Since the experimental results of section 2 and section 1, section 3 and section 4 were consistent respectively, the experimental results of measuring points in the section 2 and section 3 which shown in figure 10 were compared to analyze the wind speed increment problem. The angles of wind on the horizontal and vertical direction of the measuring points varied within ±2 degrees, which was within the errors generated by wind pulsation and installation, so it was considered that the wind was not deflected for all experimental condition. The experimental results of measuring points in section 2 differ less than 2% from the speed of trailer, indicating that the blocking effect of the area in the front of trailer could be ignored. The experimental results of measuring points in the section 3 were 9.5% larger than the speed of trail in average, and the wind speed of all measuring points were close to each other, forming a stable wind speed increment interval, indicating that the wind field in the bottom of the trailer had obvious blocking effect. Therefore, in order to evaluate the influence of blocking effect on the experiment, resistant experiment should be carried out in section 1 and section 2 (front of the trailer), section 3 and section 4 (bottom of the trailer) respectively.

4.2. Research on the experimental results of the forward and trailer bottom
Figures 11-13 showed the experimental results in the front and bottom of the trailer, and figure 14 showed the relative errors of experimental results under two conditions. Error (%) = (forward-bottom)
/ bottom * 100%. It should be noted that Δ(displacement) and L(length) adopted in this paper were constant values for the dimensionless treatment of experimental and numerical results. The results of the low speed experiment (V=6.5 m/s) showed that the error of drag, the heave and the trim angle of model in the front and bottom of the trailer were within 2.1%. At mid-high speed (V≥8 m/s), comparing the results of model in the bottom of trailer, the model in the front of the trailer showed greater drag, bigger trim angle and smaller heave amplitude. In the figure 11, the trim angle of model in the front of trailer was maintained at about 8.5°, while the trim angle obtained from the model in the bottom of trailer decreased with the increase of the speed. The relative error of trim angle under the two conditions increased from 5.1% gradually with the increasing speed. As the speed was greater than 12m/s, the tail of the model in the bottom of the trailer began to leave the water, while the tail of the model in the front of the trailer was still under the water, so the errors of trim angle and drag (shown in figure 13) under the two conditions were significant when the speed was above 12m/s. In the figure 12, the heave amplitude obtained from model in the front of the trailer was 5.5% smaller than the bottom of the trailer in average. In the figure 13, the drag obtained from model in the front of the trailer was 7.2% bigger than the bottom of the trailer in average.

The experimental results under the two conditions were in good agreement at low speed, while the error of the experimental values under the two conditions was more than 5% at mid-high speed. It could be seen that the influence of blocking effect was obvious at the mid-high speed.

4.3. Blocking effect of aviation high-speed towing tank
Unlike the general ship test, the effect of air field on the seaplane couldn’t be ignored at the mid-high speed. Therefore, the degree of blocking effect of water and air on the model test during the mid-high speed was necessary to be further studied by CFD method. The experimental results of air field
showed that the speed of wind in the front area of the trailer was consistent with the theoretical value. By comparing the computed results of the model in the front of the trailer and infinite domain, the blocking effect of water in the model towing was studied. According to figure 15 (a) and (b), the difference of drag, trim angle and heave amplitude of the model in the front of the trailer and infinite domain was nearly ignored, the average of which was less than 2%. figure 16 showed that the distribution of wave system under the two conditions were basically the same at the speed of 11 m/s, indicating that the hydrodynamic of model weren’t affected by the side wall and shallow water effects. Analyzing as the energy transfer, the larger the wave fluctuation of the model, the more energy it needed to consume, then the energy was ultimately reflected as the form of drag. In this respect, the similarity of drag results computed from the two conditions were rationality. Li Guangnian pointed out that when the blocking ratio was less than 0.2%, the blocking effect could be ignored[9]. The blocking ratio between the model and tank adopted in this paper was 0.098%. The computed results of the model in the infinite domain and the front of the trailer were very similar, which was consistent with Li Guangnian’s theory, accordingly, the blocking effect of water on the seaplane in aviation high-speed towing tank can be ignored.

![Figure 15. Computed drag (a) and attitude (b) under the different conditions](image)

![Figure 16. Comparing of wave system at different conditions](image)

![Figure 17. Comparing of computed lift of different parts.](image)

The drag and attitudes were given by the towing test of seaplane in the front and bottom of the trailer, and numerical simulations was conducted under the same conditions. By studying the computed results of each part of the model under the two conditions, the influence of the blocking effect of the air field on the hydrodynamic performance of the model had been further studied. In figure 17, considering that the speed of wind in the bottom of the trailer was 9.5% higher than that in the front of the trailer in average, the aerodynamic lift of the wing+flaps in the bottom of the trailer was obviously greater than that in the front of the trailer. In figure 18, it can be seen that the
hydrodynamic moments of the hull were opposite to the aerodynamic moments generated in horizontal tail+elevator and wing+flaps, and the aerodynamic moment was significantly bigger when the model was located at the bottom of the trailer than in the front of the trailer, and the difference increased with the increase of the speed. In summary, due to the blocking effect of the air field, compared with the model in the front of the trailer, the model in the bottom of the trailer suffered more aerodynamic lift and bigger bow moment, resulting in larger heave amplitude, smaller pitch angle, in further smaller wet surface of model and drag.

4.4. Analysis of influence of geometric parameters of trailer chassis on blocking effect

The hydrodynamic performance of seaplane under different shape of trailer chassis were computed at the speed of 11m/s by changing the length, breadth and gap of the bottom of trailer, studying the influence of geometric size of trailer chassis on blocking effect. The sketch of the geometric parameters of the trailer chassis was shown in the figure 19. It should be noted that the geometry of the trailer chassis was symmetrically changed by taking the geometric center of chassis as the origin, and the geometric center of the model was always directly below the geometric center of the trailer chassis.

Figure 20(a) showed the relationship between the hydrodynamic performance of the model and the width of the trailer chassis when $L = 9.6$m and $B_{gap} = 0$m. Figure 20(b) showed the relationship between the hydrodynamic performance of the model and the breadth of the trailer chassis when $B = 6.5$m and $B_{gap} = 0$m. Figure 20(a) showed the relationship between the hydrodynamic performance of the model and the breadth of the gap when $L = 9.6$m and $B = 6.5$m.

We can observed from these figures that when the breadth was larger than 3 m and the length was longer than 4.5m, the computed results of the model remained basically unchanged, which were basically consistent with the computed results obtained from the actual size of the trailer chassis. When the breadth was less than 3m and the length was less than 4.5m, the drag and trim angle...
decreased obviously with the increase of geometric parameters, but the heave amplitude increases accordingly. With the increase of the breadth of gap, the drag and trim angle increased, and the heave amplitude decreased. When the breadth of gap exceeded 2.5m, the computed results basically remained unchanged.

In summary, when the breadth of trailer chassis was less than 3m, the length of trailer chassis was less than 4.5m or the breadth of gap was less than 2.5m, the degree of blocking effect of air field increased with the increase of geometric variables, but when the size of chassis exceeded these specific values, the degree of blocking effect remained its maximum, and kept basically unchanged.

5. Conclusion

Experiment and CFD simulation were conducted in this paper to study the blocking effect of aviation high-speed towing tank. From the results of these works, the following conclusions could be derived:

1. The experiment of air field showed that the blocking effect of area in the front of the trailer could be ignored, while the blocking effect of area in the bottom of the trailer was obvious.

2. The experiment of the model in the front and bottom of the trailer showed that the experimental results obtained from two conditions were in good agreement at low speed, but the error of the results of model at two conditions obtained at mid-high speed was more than 5%. The blocking effect was ignored at low speed but obvious at mid-high speed.

3. Comparing the computed results of the model in the infinite domain and front of the trailer, it could be seen that the blocking effect of water on the model can be ignored. By analyzing the computed results of each part of the model in the front and bottom of the trailer, the blocking effect of air field had obviously influence on the hydrodynamic performance of the model in the bottom of trailer.

4. The computed results of hydrodynamic performance of seaplane under different trailer chassis shapes showed that when the breadth of trailer chassis was less than 3m, the length of trailer chassis was less than 4.5m or the breadth of gap was less than 2.5m, the degree of blocking effect of air field increased with the increase of geometric variables, but when the size of chassis exceeded these specific values, the degree of blocking effect remained its maximum, and kept basically unchanged.

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