Investigation on the Scale Effect of Air Tanker with Pumping System resistance components

Zhijian Xiao¹, Junqing Xiao², Rong Jiang¹, Bing Wu¹, Yuxiang Wan³,*

¹AVIC Special Vehicle Research Institute, Key Aviation Scientific and Technological Laboratory of High Speed Hydrodynamic Jinmen, China
²Shijiazhuang Tiedao University Shijiazhuang, Hebei, China
³School of Naval Architecture & Ocean Engineering, Huazhong University of Science and Technology, Wuhan, Hubei, China

*Corresponding author e-mail: wanyuxiang@hust.edu.cn

Abstract. The ship viscous flow field of multiple scale models including real scale was calculated by using RANS method and SST k-ω model. The reliability of the method was verified by comparing the computed results with the experimental results at different scales. By studying the scale effect of various resistance components of a air tanker, it was found that the scale effect of total resistance and water resistance of the model with the pumping system was obvious, and the dimensionless air resistance coefficient almost kept constant at the studied range of Reynolds number. The additional resistance coefficient generated by pumping system increased with the increase of Reynolds number, and the resistance coefficients of the baler increased with the increasing Reynolds number.

Key words: air tanker; scale effect; viscous flow field; resistance coefficient

1. Introduction
The resistance prediction of amphibious aircraft is mostly based on model test, which is generally carried out under the condition of equal Froude number, and the equal Reynolds number can't be guaranteed. In order to solve the problem of scale effect, a series of extrapolation empirical formulas, such as Froude method and cubic method are born in practical engineering[1]. Although these methods have strong practicability in engineering, with the development of shipbuilding industry and the appearance of various energy-saving devices, people are trying to find a new prediction method of ship resistance which can directly give the flow field information under the real ship Reynolds number.

With the rapid development of computer technology and numerical methods, CFD method can not only fully consider the viscous action of the fluid, but also take the nonlinear factors of the fluid into account. Compared with the traditional potential flow theory, CFD method shows great advantages. In recent years, CFD technology has been used to directly calculate the hydrodynamic performance of real scale objects. Ligtelijn, J.T (2004) corrected the scale effect of propeller cavitation by comparing model test results with simulation results [2]. Hochkirch and Mallol (2013) studied and analyzed this problem in detail through a series of calculation results, and pointed out that the study on real scale was very necessary, especially for hull with attached body [3]. Castiglione (2013) studied the motion response of
high-speed catamaran in regular waves at three different velocity points. After that, the seakeeping performance of the same catamaran at different Froude numbers was simulated in the case of both frontal and oblique waves [4]. Andre Kleinwa et al. (2017) used the CFD method to study the problem of propeller excitation force and noise at real scale, and verified the accuracy of the CFD method by comparing the test results with simulation results [5].

This paper was organized as follows: Section 2 given the studied air tanker properties and the computational parameters of the air tank at different scales. Then, in Section 3, the resistance conversion methods were explained. Following this, in Section 4, computed results including validation and verification studies were discussed. Finally, in Section 5, the main results drawn from this study were summarized.

2. Geometry and mesh generation

2.1. Geometry

In this paper, the bare body and the model with pumping system of the air tanker were taken as the research objects, as shown in figure 1 and 2. In order to study the scale effect of the resistance components of the aircraft for the two models, a series of different scale ratios were designed based on the Froude similarity. Considering that the air resistance accounts for a large proportion at high speed and compute the air resistance accurately, the boundary layer of each control surface was set separately. The average value of wall y+ was 5. The computational parameters of the air tanker at different scales were shown in Table 1.

![Figure 1. Typical features of air tanker.](image1)

![Figure 2. The bare model (a) and the model with pumping system (b).](image2)

| λ  | Re (10⁶) | Y+ (average) | Growth Rate of boundary layer | Number of layers | Grid numbers (million) |
|----|----------|--------------|-------------------------------|-----------------|-----------------------|
|    | hull     | control surface |                                |                  | Bare hull | Model with pumping system |
| 20 | 3.01     | 100          | 5                              | 1.3              | 12        | 803    | 987 |
| 10 | 17.01    | 100          | 5                              | 1.3              | 12        | 829    | 1025|
| 8.5| 22.48    | 100          | 5                              | 1.3              | 12        | 865    | 1108|
| 8  | 23.77    | 100          | 5                              | 1.3              | 12        | 891    | 1197|
| 4  | 67.23    | 150          | 5                              | 1.2              | 18        | 1326   | 1631|
| 2  | 190.15   | 150          | 5                              | 1.1              | 18        | 1852   | 2144|
| 1  | 537.82   | 200          | 5                              | 1.1              | 28        | 2699   | 3330|

2.2. mesh generation

STAR-CCM+ was adopted for grid generation, as shown in fig. 3(a). Due to the different dimensions of each model, there were some differences in the number of grids, including the thickness of boundary layer and the number of layers. In the specific calculation process, the boundary layer settings adopted by the ship and each control surface were shown in table 1. The size of computing domain was: 1.0L≤x≤4.5L, 1.5L≤y≤1.5L, 1.0L≤z≤1.0L. Due to the geometrical symmetry of the model, a semi-machine model was adopted for simulation. The downstream outlet was adopted pressure outlet.
Symmetric surface boundary conditions were used for upper boundary, side boundary and middle surface. The wall boundary conditions with no-slip were defined on the hull surface, and the boundary condition settings of the calculation domain were shown in fig.3 (b).

In this paper, RANS method was adopted to solve the calculation, and SST k-ω turbulence model was adopted with reference to Yongliang Wang[6]. The governing equations were discretized by the second order windward finite volume method (FVM). The convection term was discretized by the second-order upwind scheme, and the time-reciprocal term by the third-order Euler scheme. Free surface was captured by two-phase fluid volume (VOF) technique.

![Figure 3. Mesh distribution (a) and boundary condition (b).](image)

3. Resistance conversion methods
The ship model and the real ship couldn’t satisfy the same Reynolds number and Froude number at the same time, so the ship model resistance test was actually only carried out under the condition of keeping the Froude number equal. The total resistance of the ship was expressed as:

\[ R_{ts} = R_{hs} + R_{as} \] (1)

Where, \( R_{ts} \) was the total resistance of the real machine, \( R_{hs} \) was the total water resistance of the real machine, and \( R_{as} \) was the air resistance of the real machine.

\[ R_{hs} = R_{fs} + R_{rs} + \Delta R_{s} \] (2)

According to Froude conversion method, the residual resistance coefficient was only related to Froude number, \( C_{rs} = C_{rm} \).

Therefore, the total resistance of the actual ship was:

\[ R_{ts} = (R_{tm} - R_{am} - R_{fm})\lambda^3 + R_{fs} + R_{as} + \Delta R_{s} \] (3)

The frictional resistance was determined by the following equation:

\[ R_{fs} = 0.5(C_{fs} + \Delta C_{fs})\rho_s s_v v_s^2 \] (4)

\[ C_{fs} = 0.075/(\log Re - 2)^2 \] (5)

Where, \( C_{fs} \) was the friction resistance coefficient of a real ship, \( \Delta C_{fs} \) was the roughness subsidy of the actual ship. \( s_v \) was wet surface area (m²) of real machine. \( v_s \) was the running speed of the real machine (m/s).

Air resistance was determined by the following equation:

\[ R_{as} = 0.5s_{as} v_s^2 C_x \] (6)

Where, \( s_{as} \) was airfoil area (m²), and air resistance coefficient \( C_x \) was air resistance curve, which was obtained by interpolation of air resistance coefficient curve obtained from wind test of non-dynamic model.
4. Results and discussion

4.1. Verification and Validation
The viscous flow field of bare model of air tanker were computed at typical Reynolds numbers, to validate its numerical method. As shown in table 2, the relative errors of the resistance obtained by the simulation and test results were 7.33% and 8.10% at λ=10 and 8.5, respectively. At λ=1, according to equation (3), the conversion of $\psi_t$ obtained from the test value was 0.155, with a relative error of 6.84% comparing the simulation. The dimensionless amplitude comparison of calculations and experiments at Y=0.08Lpp were similar as shown in figure.4. Therefore, the numerical method adopted in this paper was reasonable and reliable.

| $\lambda$ | Re($10^6$) | Method | $\psi_t$ | Error   |
|----------|-------------|--------|----------|---------|
| 10       | 17.01       | CFD    | 0.150    | 7.33%   |
|          |             | EFD    | 0.161    |         |
| 8.5      | 22.48       | CFD    | 0.148    | 8.10%   |
|          |             | EFD    | 0.160    |         |
| 1        | 537.82      | Conversion | 0.146  | 6.84%   |
|          |             |        |          |         |

Table 2. Error of $\psi_t$ of simulation and experiment

![Figure 4](image_url) Dimensionless amplitude comparison of simulation and experiment at Y=0.08Lpp.

4.2. Scale Effect of Total Resistance and Air Resistance
To investigate the scale effect of resistance components, dimensionless resistance component coefficients were defined by dividing the displacement of the air tanker. As shown in figure.5, The dimensionless coefficient of conversion value of the total resistance $\psi_{\text{conversion}}$ (observed by equation(3)), the computed dimensionless total resistance coefficient $\psi_t$, and the computed dimensionless total water resistance coefficient $\psi_h$ differed with the Reynolds numbers for bare model of air tanker. Comparing the model scale (Re = $3.01 \times 10^6$), $\psi_{\text{conversion}}$ and $\psi_t$ differed -9.30% and -8.15% at the full scale (Re = $5.38 \times 10^8$). In the process of resistance conversion, the splashing resistance was included in the total resistance, but the VOF model couldn't accurately simulate the splashing resistance, so the computed $\psi_t$ was about 9.0% smaller than the test value on average. The dimensionless air resistance coefficient $\psi_a$ of the experiment and simulation was almost constant value for all studied range of Reynolds numbers. The computed $\psi_a$ was slight smaller than that from experiment, probably because the experimental model was relatively rough.

Comparing the model scale (Re = $3.01 \times 10^6$), the computed $\psi_t$ differed -5.95% at the full scale (Re = $5.38 \times 10^8$) for the air tanker model with pumping system, and the computed $\psi_a$ was almost constant with increasing Reynolds number, as shown in figure.6.

4.3. Scale Effect of Total Water Resistance
As shown in figure.7, with the increase of Reynolds number, the total water resistance coefficient $C_h$ and friction resistance coefficient $C_f$ shown a decreasing trend, while residual resistance coefficient $C_r$...
increased. Comparing with the model scale, the $C_h$ of the bare model and the model with pumping system differed $-11.85\%$ and $-7.53\%$ at full scale, separately, while $+3.45\%$ and $+4.65\%$ for Cr. It should be noted that the bare model were adopted for all resistance coefficients in the dimensionless process.

As shown in figure 8, the friction resistance coefficient of the two model were in agreement with ITTC57 extrapolation formula. The model with pumping system was slightly 3% larger than ITTC57, and the bare model was slightly 3% smaller than ITTC57. The reduction of boundary layer thickness at high Reynolds number clearly explained the behavior of friction resistance coefficient.

As shown in figure 9, the difference of the bow wave system was relatively minor but the full scale stern wave amplitude was somewhat larger. A lower stern wave system given less radiated wave energy and therefore a lower wave resistance coefficient, so wave resistance coefficient at full scale was bigger than model scale. It could be seen from the researches [7][8] that the wave resistance accounted for the largest proportion of residual resistance for high-speed ship, therefore the residual resistance coefficient shown increasing trendy with Reynolds number.

4.4. Scale Effect of additional resistance generated by pumping system
The additional resistance coefficient $\Delta C_t$ generated by pumping system was defined as the difference of total resistance coefficient of the bare model and the model with pumping system. As shown in figure 10, $\Delta C_t$ increased with the increase of Reynolds number. $\Delta C_t$ at full scale was 10.62% bigger than model scale. The $\Delta C_t$ had obvious scale effect.
By analyzing the resistance component of the pumping system, the resistance of the baler accounts for about 90% of the resistance of the pumping system. As shown in figure 12, the pressure coefficient distribution in the baler was obviously bigger than outside, the force of the baler was subjected to $F_x$ and $F_z$. The figure 12 shown that the force of the baler varied with Reynolds number. The $C_x$ and $C_z$ (negative z-axis) of the baler increased with the increasing Reynolds number, therefore, the additional resistance coefficient $\Delta C_t$ increased with increasing Reynolds number.

**Figure 9.** The stern wave system of three hull forms at model and full scale.

**Figure 10.** The additional resistance coefficient at different Reynolds number.

**Figure 11.** Resistance coefficient of the baler at different Reynolds number.

**Figure 12.** The pressure coefficient at model and full scale.
5. Conclusion

From the results of these works, the following conclusions could be derived:

1) For the bare model and the model with pumping system of the air tanker, the computed $\psi_t$, $\psi_h$ decreased with the increase of the Reynolds number, while $\psi_a$ kept constant. Total resistance and total water resistance shown the obvious scale effect, but the air resistance coefficient was almost constant value.

2) With the increasing of Reynolds number, the residual resistance coefficient shown a increasing trend. The friction resistance coefficient of the two model were in agreement with ITTC 57 extrapolation formula. The difference of the bow wave system was relatively minor but the full scale stern wave amplitude was somewhat larger, so wave resistance coefficient at full scale was bigger than model scale.

3) The additional resistance coefficient increased with the increase of Reynolds number. The additional resistance coefficient had obvious scale effect.

Acknowledgements

The research reported in this paper was supported by 605 research institute of china. This support was gratefully acknowledged.

References

[1] YIN Chonghong, Wu Jianwei. Model- and full-scale VLCC resistance prediction and flow field analysis based on IDDES method. Chinese journal of hydrodynamics, 2016, vol.31, No.3.

[2] Hochkirch, K., Mallol, B. On the importance of full-scale CFD simulations for ships. In: Proceedings of the 12th International Conference on Computer Applications and Information Technology in the Maritime Industries, 2018, pp 85-95.

[3] Castiglione, T., Sadat Hosseini, H. CFD simulation for sea keeping of Delft catamaran in regular head and oblique waves. In: Proceedings of the 12th International Conference on Fast Sea Transportation, Amsterdam, the Netherlands, 2013.

[4] Ligtelijn, J.T, Van Wijngaarde, H.C.J. Correlation of Cavitation: Comparison of Full-Scale Data with Results of Model Tests and Computations, SNAME Maritime Technology conference, Washington, USA, 2004.

[5] Andre Kleinwaechter, Katrin Hellwig-Rieck. Full-scale total wake field PIV-measurements in comparison with ANSYS CFD calculations: a contribution to a better propeller design process, J Mar Sci Technol (2017) 22: 388 – 400.

[6] Yongliang Wang. Study of the Algorithm for Dropping Water with Air Tanker [J]. Microcomputer Information Journal, 2012, 9 (8): 208-215.

[7] Li Yun. An investigation on the resistance of high speed trimarans [J]. Journal of Ship Mechanics, 1007-7294(2007)02-0191-08.

[8] ZHOU Chongjian. Research of Resistance Estimation Method for High-Speed Catamaran [J]. SHIPBUILDING OF CHINA, 1000-4882 (2014) 04-0026-07.