Wind-induced numerical simulation and analysis of airship transport process

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Abstract. Aiming at the problem that the stability of airship’s posture is destroyed by turbulent flow when the airship leaves the large factory building, a Computational Fluid Dynamics (CFD) numerical simulation method is used to simulate the condition that airship transport process in different angle of the incoming flow, and the surface wind load and equivalent force/moment of airship in variation with transport distance are acquired. The results shows that the turbulent flow of large factory building causes the variation of surface wind load of airship in the transport process, and the equivalent force/moment acting on airship body center show a certain degree of fluctuations; In 60 and 90 degree of the incoming flow, compared with other inflow angles, the distance affected by the turbulent flow of large factory building is shorter, the equivalent force and moment acting on the airship body center are larger, in the process of airship transport. The simulation results provide an effective reference for the safety of airship transport process.

1. Introduction

Airship is a kind of aircraft which can fly by air buoyancy and propulsion system[1]. Airship can stay in the air for a long time with the low cost of manufacturing and flying, and it has good concealment performance and a large payload. Airship is widely used in communication relay, early warning detection, electronic countermeasures, intelligence investigation and other fields.

The capsule of airship, especially for the blimp, is usually made of flexible membrane material. Due to the small stiffness of airship, its shape is very sensitive to the change of incoming flow, thus assembling and inflating in the large factory building, and then transported to the outside for launching. With the increasing requirements of airship flight and dwell time, the volume of modern airship tends to be large, and generally can reach 104m3 orders of magnitude. The huge volume makes the airship vulnerable to the influence of the flow in all directions and the disturbance of large factory building, which makes it possible for the accident that the airship collides with the large factory building, thus it is of practical and important significance to study the transport process of airship. Computational Fluid Dynamics (CFD) is a technique for numerical simulation and analysis of physical phenomena such as fluid flow and heat transfer. In this paper, a airship numerical calculation model is established and a fluid simulation software is used to simulate the airship surface wind load, and then the airship aerodynamic parameters are obtained. The airship aerodynamic parameters acquired from simulation
are compared with existing semi-empirical model, and then the influence of large factory building on airship transport process is analyzed.

In recent years, the research on airship aerodynamic performance is in-depth. Based on the potential flow theory, M. Munk[2] gave the aerodynamic force on the cross section of airship at low angle of attack. Considering the influence of atmospheric viscosity on airship aerodynamics, J. Allen and W. Perkins[3] modified the existing aerodynamic model. D. Delaurier[4] etc considered the effect of the empennage on the hull and got more perfect aerodynamic estimation expression. P. Jones[5] simplified the interaction between hull and empennage as two effective coefficients $\eta_k$ and $\eta_f$, and gave the semi-empirical formula of aerodynamic force for airship flying at angle of attack. In order to describe the aerodynamic force of the airship in full state, B. Mueller[6] expressed the aero-dynamic force calculation formula of the rigid airship of which center of gravity and center of inertia do not coincide as a six degree of freedom equation, and considered the influence of the added mass and inertia, but did not consider the reciprocal of motion. Based on the wind tunnel test data of German Lotte-airship, Miao Jinggang revised the existing theory, gave the six degree of freedom aerodynamic calculation model of general configuration airship, and identified the parameters of Lotte-airship aerodynamic calculation model by using the least square method[7]. The identification results prove the applicability of the model. The above literatures mainly focus on the analysis of aerodynamic characteristics of airship in cruising or lingering conditions, but there is a lack of in-depth research on the aerodynamic resistance of airship in the process of transport.

2. Semi-empirical aerodynamic model of airship

The semi-empirical model of airship aerodynamic calculation is given in [7]. The finalization and identification of the model are mutually verified and finally determined by referring to various literatures. It can basically be used to describe the aerodynamic force of airship in stationary state.

The semi-empirical aerodynamic model of airship defines the body center of airship as the origin of body coordinate system OXYZ. The definition of coordinate system: The angle of attack and sideslip angle comply with the GB/T144101-93. The components of aerodynamic force and aerodynamic moment of airship in the body coordinate system are $X$, $Y$, $Z$ and $L$, $M$, $N$. The shape and force of airship are shown in Figure 1.

![Figure 1 Outline and aerodynamic diagram of airship.](image)

The aerodynamic semi-empirical model of airship is described as follows:

\begin{align}
X &= -Q_0 \left[ C_x \cos^2 \alpha \cos \beta + C_{x\gamma} \sin(2\alpha) \sin(\alpha/2) \right] \\
Y &= -Q_0 \left[ C_y \cos \beta/2 \sin(2\beta) + C_{y\gamma} \sin(2\beta) \cos \alpha \sin(\alpha/2) \right] \\
Z &= -Q_0 \left[ C_z \cos(\alpha/2) \sin(2\alpha) + C_{z\gamma} \sin(2\alpha) \cos \beta \sin(\alpha/2) \right] \\
L &= -Q_0 \left[ C_L \cos(\alpha/2) - \delta_{\alpha \alpha} + \delta_{\alpha \beta} + \delta_{\alpha \gamma} \right] \\
M &= -Q_0 \left[ C_M \cos(\alpha/2) \sin(2\alpha) + C_{M\gamma} \sin(2\alpha) \cos \beta \sin(\alpha/2) \right] \\
N &= -Q_0 \left[ C_N \cos(\beta/2) \sin(2\beta) + C_{N\gamma} \sin(2\beta) \cos \alpha \sin(\alpha/2) \right] \\
\end{align}
Where $Q_\infty$ is the dynamic head in aerodynamic calculation, $Q_\infty = \frac{1}{2} \rho V^2$, $V_\infty$ is airspeed of airship, $\rho$ is the atmospheric density, $\alpha$ and $\beta$ are attack angle and sideslip angle respectively, $C_{x1}$, $C_{x2}$, ..., $C_{x4}$ are aerodynamic coefficient, and the specific calculation method of aerodynamic coefficient can refer to [7], $\delta_{elvl}$, $\delta_{elvr}$, $\delta_{rudr}$, $\delta_{rudb}$ are left, right elevators and up, down rudders.

3. Accuracy verification of numerical simulation

For complex flow problems, the numerical simulation method has the advantages of low costing, time consuming, and easy to obtain the data in the flow field. In order to verify the reliability of the simulation results, the aerodynamic characteristics of Lotte-airship are analyzed by the CFD simulation software ANSYS FLUENT, and the simulation results are compared with the calculation results of the semi-empirical model.

3.1. Modeling and meshing of airship

The Lotte-airship, developed by Stuttgart University in Germany, is taken as the sample to establish the simulation model. The main parameters of the Lotte-airship are as follows: The hull length $L=16m$, the maximum diameter $D_{\text{max}}=4m$, the volume of airship $V=109m^3$, the slenderness ratio $L/D=4$, the empennage is a cross configuration. The 3D simulation model of airship is shown in the Figure 2.

![Simulation model of airship.](image)

Considering the blocking rate and the full development of the flow, the distance between the outflow boundary of the computational domain and the airship should be more than 10 times of the airship height. The size of the computational domain is $120m \times 80m \times 40m$.

Grid generation software ICEM CFD is used to mesh airship and computing domain. In order to make the results more accurate and improve the efficiency of mesh generation, the nested mesh generation method is used: The unstructured tetrahedral grid is used in the surrounding area of the airship, the structured hexahedral grid is used in the outer area, and the prism grid is set in the near grid wall. The symmetric section grid is shown in Figure 3. The number of the final volume mesh cell is 515907.

![Symmetric section grid.](image)

3.2. Setting of boundary conditions

The Reynolds number of the flow field studied in this in the order of $10^6$, so it can be judged that the flow is turbulent. The numerical calculation model is imported into the fluid analysis software for simulation, and the standard $k-\varepsilon$ model is used for calculation according to the turbulence simulation
method. The standard k-ε model is based on two transport equations to solve k and ε. The coefficients are given by empirical formula. It is widely used and the amount of calculation is moderate, and has a lot of data accumulation. The convergence and calculation accuracy can meet the requirements of general engineering calculation. As for the setting of boundary conditions, the airship surface and ground are set as the wall boundary conditions. Wall boundary conditions are used to limit the fluid and solid regions. The flow surface of the external flow field is set as the velocity inlet, and the velocity inlet boundary condition is used to define the flow velocity and the flow property related scalar of the flow inlet. The outlet of the outflow field is set as the outflow boundary condition. When the velocity and pressure at the exit are unknown before solving the flow problem, the exit boundary condition can be used. The surface and the side of the external flow field are set as symmetrical boundary conditions. When the flow in the field and the boundary shape have mirror symmetry, the symmetrical boundary condition can be set in the calculation.

3.3. Simulation results and verification

The aerodynamic parameters calculated by the semi-empirical model of Lotte-airship are basically consistent with the wind tunnel test data, which can be used as a reference for the simulation results [8]. In order to verify the reliability of the simulation results, the numerical simulation results are compared with the aerodynamic parameters calculated by the semi-empirical model of airship aerodynamics.

On the condition that the rudder angle is 0 degree and the incoming wind direction is -30~30 degrees, and the drag coefficient, lift coefficient and pitching moment coefficient calculated by numerical simulation and semi-empirical model are compared. The results are shown in Figure 4 to Figure 6.

![Figure 4 Drag coefficient curve.](image1)

![Figure 5 Lift coefficient curve.](image2)

![Figure 6 Pitching moment coefficient curve.](image3)

The results show that the drag coefficient, lift coefficient and pitching moment coefficient obtained by the numerical simulation method are basically consistent with the results obtained by the semi-
empirical model. The simulation results have high reliability, so the numerical simulation method can be applied to the simulation of wind load in airship transport process.

4. Wind load simulation of airship transport process
In the process of airship transport, the turbulence around the large factory building will affect the airship surface flow field. Air separation, reverse pressure gradient and separation vortex caused by hull and tail vortex will cause the change of wind load on airship surface[9]. The three-dimensional model of integrated airship and large factory building is established to simulate the surface wind load of airship in the transport process under different incoming flow.

4.1. Establishment of simulation model
The simulation models of the airship and the large factory building under different working conditions are established, and the right-hand system is established with the intersection of the plane of large factory building exit and the airship longitudinal axis as the coordinate origin, as shown in Figure 7. Taking a test airship as the simulation model, the length of the test airship is 80m, the maximum diameter is 30m, and the X-shaped empennage structure is adopted. The height between the airship body center and the ground is 20m. The length, width and height of the large factory building are set as 266m, 140m and 117m respectively. According to the external dimensions of airship and large factory building, the size of calculation domain is set as 3000m×2400m×1800m, so that the flow can be fully developed.

According to the method in Section III, topological computational domain is established, and the boundary conditions and calculation model are set. The turbulence during airship transport belongs to low-speed incompressible flow, and the Navier-Stokes equations for the Reynolds mean of incompressible flow and the k-ε turbulence models are used. The equation is discretized by finite volume method and the convection term is discretized by second order upwind scheme. The diffusion term adopts the central difference scheme, and the velocity pressure coupling method adopts SIMPLE algorithm. Figure 8 shows the grid division of computing domain for surface wind load simulation in the airship transport process.

4.2. Numerical calculation and result analysis
Conditions set: The wind speed is constant at 4m/s, and the included Angle between the wind speed and the airship axis is set as θ. When the wind speed is in the negative direction of z axis, θ is 0 degrees. θ rotates clockwise and every 30 degrees for a working condition. Since the model is symmetric about the yOz plane, the range of θ can be taken as [0,180]. It can realize the simulation calculation under different incoming flow angles. The airship transports at a constant speed of 1m/s, and the distance between the foremost point of the airship and the origin of the coordinate system is taken as the transport distance. Figure 9 is the simulation working condition diagram of airship transport process.
Figure 9  Simulation working condition diagram of airship transport process.

4.2.1. Characteristics of surface wind load during airship transport.

According to the simulation model of airship transport process, the wind pressure distribution on the airship surface is calculated when the transfer distance is 0m, 40m, 80m, 120m at 90 degree inflow condition. The simulation results are shown in the Figure 10. to Figure 13.

Figure 10  Surface pressure nephogram at transfer distance of 0m.

Figure 11  Surface pressure nephogram at transfer distance of 40m.
Due to the influence of wind field disturbance of large factory building, the wind pressure distribution on the surface of airship will show a certain variation law during the transport process. The positive pressure area of airship surface generally appears on two side of airship; the negative pressure area generally appears in the upper part of the airship, and the lower part and the front end of the head. With the increase of transfer distance, the positive pressure area on the airship surface gradually shifts from the airship head to the middle and tail of the airship, and the pressure difference on the hull surface increases gradually.

4.2.2. Numerical simulation results of equivalent force and moment.
In the post-processing software, the distributed wind pressure on the airship surface is equivalent to the resultant force and moment acting on the airship body center along the x, y, z axes, and the change of resultant force and moment of airship in different incoming flow directions can be gotten, as shown in Figure 14 to Figure 27.
Figure 14  Equivalent force curve at incoming flow of 0 degree.

Figure 15  Equivalent moment curve at incoming flow of 0 degree.

Figure 16  Equivalent force curve at incoming flow of 30 degree.

Figure 17  Equivalent moment curve at incoming flow of 30 degree.

Figure 18  Equivalent force curve at incoming flow of 60 degree.

Figure 19  Equivalent moment curve at incoming flow of 60 degree.
Figure 20  Equivalent force curve at incoming flow of 90 degree.

Figure 21  Equivalent moment curve at incoming flow of 90 degree.

Figure 22  Equivalent force curve at incoming flow of 120 degree.

Figure 23  Equivalent moment curve at incoming flow of 120 degree.

Figure 24  Equivalent force curve at incoming flow of 150 degree.

Figure 25  Equivalent moment curve at incoming flow of 150 degree.
It can be seen from the simulation results in the process of airship transport that the equivalent force and equivalent moment acting on the airship body center fluctuate to a certain extent, and the variation of equivalent force and moment is different under different incoming flow angles, with the increase of transport distance. Under the condition of 60 degree and 90 degree inflow, the equivalent force and equivalent moment of airship fluctuate obviously within 80m distance, as the results of the disturbance of large factory building. When the airship leaves the disturbance range of the large factory building, the three-dimensional resultant force and moment tend to be stable. In the case of 0 degree inflow, the equivalent force in z-axis direction tends to 0, and the equivalent force and moment in other directions fluctuate obviously in the process of transport. Except for the case of 0 degree flow, the equivalent moment on the z-axis is basically 0, and the equivalent force and moment in other directions are in the state of fluctuation. The extremum of equivalent force and moment appear in the case of 60 degree, the extremum of equivalent force is 83058 N and the extremum of equivalent moment is 618746 N·m.

5. Conclusions

- During the transport process, the positive pressure area on the surface of airship gradually transfers from the airship head to the middle and tail of the airship, and the pressure difference on the surface of the airship increases gradually.
- In the process of airship transport, the wind load on the airship surface will change due to the disturbance of large factory building, and the equivalent force and moment acting on the airship body center will fluctuate to a certain extent. The variation of equivalent force and moment of airship is different under different incoming flow angles.
- When the inflow is 60 degree and 90 degree, the distance affected by the disturbance of large factory building is short, and equivalent force and moment acting on the airship center are large in the region affected by the disturbance.

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