VI International Conference on Textile Composites and Inflatable Structures
STRUCTURAL MEMBRANES 2013
K.-U.Bletzinger, B. Kröplin and E. Oñate (Eds)

NUMERICAL ANALYSIS OF AEROELASTIC CHARACTERISTICS OF AIRSHIP ENVELOPE

HUIFENG. TAN, LIUYI. YANG AND JIANZHENG. WEI

Science and Technology on Advanced Composites in Special Environments Laboratory
Harbin Institute of Technology
Harbin, 150080 Heilongjiang, China
e-mail: tanhf@hit.edu.cn, yangliuyi439@163.com, weijz@hit.edu.cn
web page: http://www. hit.edu.cn

Key words: Airship, Airship Envelope, Aeroelastic Characteristics, Numerical analysis.

Summary. Stratospheric airship has great advantages, such as long-endurance, large coverage area, low-cost and so on, these advantages make airship be an ideal stratospheric platform and become highly valued. Airship envelope is a large inflatable membrane structure. As a key component, the envelope features flexible and large displacement. There is strong coupling between envelope structure and the ambient air when airship operating in the high altitude sky. The coupling characteristics have great impact on the aerodynamic and structural performance of airship. Aiming at the aeroelastic characteristics of the envelope structure, a fluid-structure coupled computational method is presented basing on a finite element program. As an example, the envelope structure of airship is computed and the S-A turbulent model is used. The envelope drag coefficient under different attack angle is computed. The contrast between experimental results coming from reference paper and numerical results highlight the correctness of this method. With the developed computational approach, the NPL envelope is also analyzed. The changes of length to diameter ratio, max cross section location and Reynolds number are studied and the aeroelastic characteristics of flexible envelope are analyzed. These results can give some valuable information for precise forecast of the overall airship performance.

1 INTRODUCTION

Airship is a kind of lighter than air aircraft. The stratosphere is the earth's atmosphere from the tropopause top to the 50 km height. Airship voyaged in this region has the advantages of long endurance, large converge area and low cost and so on. Several countries are developing stratospheric airship project at present, such as the HiSentinel airship from the United States of America has conducted 3 stratospheric flight tests. Considering the harsh operating condition, the stratospheric airship technology still needs some further study.

There is a strong coupling characteristic between the flexible envelope structure and the external flow field. In order to guide the airship design, many scholars have done some researches on accurate calculation of the airship aerodynamic characteristics. Using a numerical method based on the Arbitrary Lagrangian Eulerian method, Omari[1] carried out some research on the static aeroelastic characteristics of an ellipsoid null in inviscid low Mach number flow field. Basing on ABAQUS software to calculate the stress and deformation of the structural field, and using VSAERO software to calculate airship external flow field aerodynamic loads, Bessert[2] analyzed nonlinear aeroelastic characteristics of the airship and five different coupling forms through a step-by-step coupling calculation. Due to the flexibility of the envelope of the non-rigid airship, the variation of the temperature of the inner gas will lead to its structure deformation and affect its flight altitude. Li [5] developed the structural mechanics model, thermodynamic model and dynamic model of the semi-rigid airship, basinf on which nonlinear finite element analysis is employed for geometrically nonlinear deformation of the airship upper film in consideration of thermodynamics and structural mechanics coupling. Wang[6] comprehensively taked into account influential factors of solar radiation, environmental temperature, wind speed, and constructed stratosphere solar energy airship heat-transfer model, and acquired the change principles of average temperature of airship preliminarily. Ilieva[7] et al have concentrated on a critical overview of propulsion mechanisms for airships. These induce a detailed overview of past, present, and future enabling technologies for airship propulsion. Diverse concepts are revisited and the link between the airship geometry and flight mechanics is made for diverse propulsion system mechanisms.

Now, the research on the airship aeroelastic characteristics mainly concentrated on the numerical method and its accuracy verification. Most of the airship aeroelastic characteristics is calculated based on the a coupling platform or a self-coupling procedures to achieve data exchange, however, the method according to the calculations of the flow field and the structural field in the iteration process cannot rationally adjust the calculated step. In view of the ADINA software has strong advantages on the fluid-structure interaction, basing on this software, an areoelastic calculation method is proposed, which can automatically adjust the coupled iterative calculation step and overcome the convergence and computational efficiency problem faced by general method of iterative. These results will provide some references for the calculation of the airship aeroelastic characteristics.

2 CALCULATION METHOD OF AEROELASTIC AND VERIFICATION

2.1 Calculation method of aeroelastic

In view of the excellent performance of structure and flow field numerical computing, accurate data transfer in the coupling interface and a reasonable set of coupled iterative step are the keys of the efficiency and accuracy of the calculation of aeroelastic. Based on the force equilibrium and displacement compatibility conditions of the coupling interface, the coupling interface interpolation method is shown in Figure 1. Since the step size can be automatically selected, the ADINA software provides an effective way for the aeroelastic computation.

During the numerical analysis of envelope aeroelastic characteristics, the coupling equation should be established based on the boundary conditions and the equilibrium equation of structure and flow field. Then the coupled equations should be discrete taken into account the integrated compatible condition and the distance from the coupling interface to grid node. Select the automatically step function of the ADINA, and then start the iterative solution. Convergence results can be tested by stress or displacement convergence criteria. Finally, the results considering the flow field and structural coupling can be achieved.

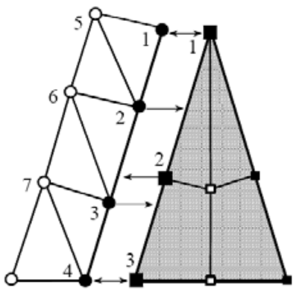

Fig.1 The numerical interpolation of coupling interface [3]

In order to simulate the flow field realistically, turbulent simulation model should be selected. Since the κ - ε turbulence model is time-consuming and difficult to convergence, while the Spalart-Allmaras (SA) turbulence model has certain advantages on the computational precision and efficiency, so the S-A turbulence model is chosen as flow calculation model. Considering the FCBI-C element enjoys the advantages such as ease of convergence, suitable for large-scale iterative solution of coupled problems, then this element is chosen as coupling calculation element.

2.2 Test case

In order to verify the accuracy of the calculation method of the envelope aeroelastic, basing on the Lotte airship which has been conducted wind tunnel tests in Germany, numerical calculations and verification are carried out in this section.

According to reference [4], the calculated model is completed. The viscous force and inner pressure, which are taken into account, have great impact on the aerodynamic performance and structural deformation while the airship is running, so the similarity principle of Reynolds number is used. The Lotte airship's experiments of 1:20 scale model is conducted in the medium-speed wind tunnel, and the volume Reynolds number is $\mathrm{Re}_V = U_\infty \cdot V^{1/3} / \nu = 3.9 \times 10^5$,in which, ν is the kinematic viscosity.

The computation flow field is rectangular parallelepiped, according to the current flow status of the envelope surface and considering the computational efficiency, the length and breadth of the flow field are set 6 and 5 times of the envelope length and maximum diameter respectively. Delaunay meshing method is used and 106,920 four-node 3-D fluid elements are divided with 20163 nodes. According to the Reynolds number similarity criteria, the inlet velocity of the flow field is 1.19m/s, and the density values is 1.225kg/m^3, the calculated dynamic viscosity coefficient is $1.7894 \times 10^{-5}\,\mathrm{N \cdot S / m^2}$. The boundary conditions are set as speed entrance and free flow export differently and the envelope surface is assumed smoothly. As the material properties of the airship model cannot be accurately obtained in the wind tunnel experiment, the pressure of the envelope is assumed 300Pa, besides, the elastic modulus of envelope is 10 GPa, Poisson's ratio is 0.38. The end of the envelope structure is constraint and the head is free along the axial direction in the calculation of structure.

Airship aerodynamic performance, especially aerodynamic drag has a great impact on energy consuming and weight of the structure. Therefore, this section starts from the volumetric drag coefficient, and verify the reliability of the airship aeroelastic computational analysis methods. Which, the volumetric drag coefficient is expressed as,

$$C_d = \frac{D}{\frac{1}{2}\rho U_\infty^2 V^{2/3}} \tag{1}$$

Where D is the aerodynamic drag of the envelope, along to the opposite direction of the flow speed, ρ is operating environment atmospheric density; U_∞ is the flow speed of far-field, V is volume calculation model.

Figure 2 shows the comparison of the calculated results and the wind tunnel experiment results under 20° angle of attack. The left figure shows that there is a certain zone of positive pressure on the windward side of the envelope head and a larger negative pressure zone on the leeward side of the envelope head. The comparisons results indicate that the numerical calculation method is variable.

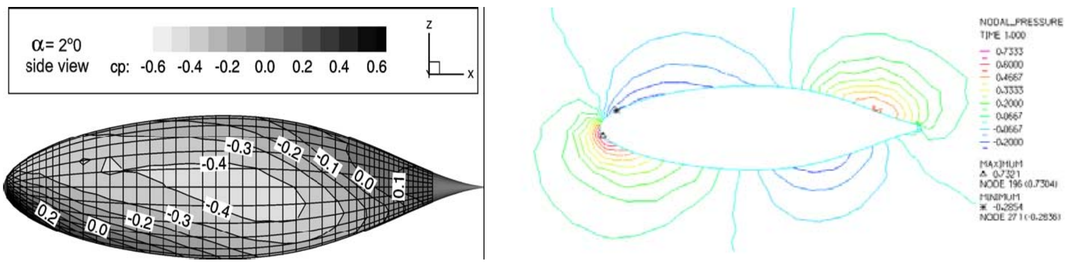

Fig.2 Comparison of pressure coefficient distribution (20° angle of attack)

To exploring the relationship between volumetric drag coefficient and the angle of attack, numerical calculation of the volumetric drag coefficient in different angles of attack are carried out. Comparison of the experimental and calculated results is shown in Fig. 3. The data in figure 3 shows that the aeroelastic numerical results and wind tunnel experiments value have a good agreement, and the volumetric drag coefficient is basically parabolic trend with the increasing of angle of attack. When the angle of attack is 0°, the calculated volumetric drag coefficient is approximately 1.24 times larger than the wind tunnel experiment result, the multiples will also slowly increase along with the angle of attack increasing, the deviation is about 29.98% when the angle of attack is 30°. Since the elastic modulus value of envelope material and the internal pressure of the envelope are unknown, the aeroelastic calculation of the volumetric drag coefficient is larger than experimental results. As the material properties parameters of the wind tunnel experiment airship model and envelope pressure data cannot be obtained accurately, these parameters in paper is given based on the experience. The comparison of numerical results and literature results show that the airship envelope numerical calculation method is feasible. At the same time, different parameters of the model, such as the internal pressure and material properties, have great influence on the aeroelastic calculation results.

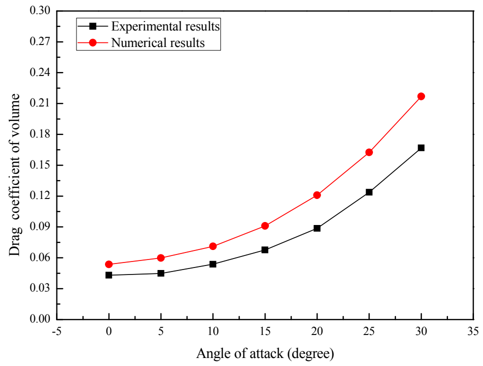

Fig.3 Drag coefficient of volume vs. angle of attack

3 INFLUENCE ANALYSES OF DIFFERENT PARAMETERS ON AEROELASTIC NUMERICAL RESULTS

In order to study the influence of different calculation parameters on the airship envelope aeroelastic results, the NPL envelope is analyzed as example and the parameters, such as the envelope slenderness ratio, the envelope maximum cross-sectional position and the Reynolds number are analyzed. The NPL envelope shape is shown in Fig. 4.

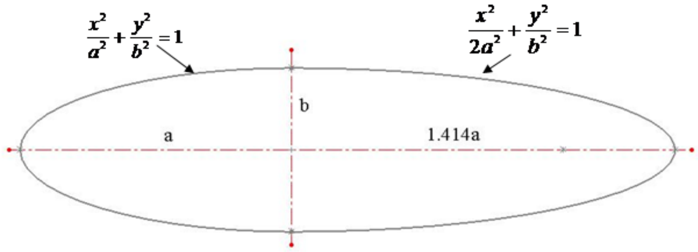

Fig.4 Shape of NPL envelope

3.1 Influence analysis of slenderness ratio

Slenderness ratio has an important influence on the whole envelope design and subsystem design. In case of fixing the envelope volume and maximum cross-sectional position of the envelope, different slenderness ratio of NPL envelope is computed. The elastic modulus of the envelope material is 4GPa, and Poisson's ratio is 0.38, the wind speed is 10 m/s. The tail of the envelope is fixed and the head has axial degree of freedom when it is computated, and the flow field boundary conditions are velocity inlet and free flow outlet with smooth wall surface.

Figure 5 shows the maximum stress contours of the structure with the 3.5 and 5.5 slenderness ratio respectively. The maximum stress is 12.12Mpa when the slenderness ratio is 3.5; however, the maximum stress is 10.47Mpa when the slenderness ratio is 5.5.

Fig.5 The contour of stress with the slenderness ratio is 3.5(left) and 5.5(right)

The envelope drag and volumetric drag coefficient versus slenderness ratio obtained by numerical calculation is shown in Fig. 6. Relational curve shows that NPL envelope has the minimum drag and volumetric coefficient when the value of slenderness ratio is about 5, and subsequently along with the slenderness ratio increasing, the envelope drag gradually increases.

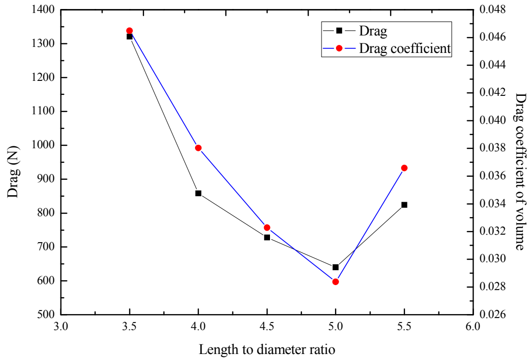

Fig.6 The envelope drag and volumetric drag coefficient vs. slenderness ratio

3.2 Influence analysis of the position of maximum cross section area

As to the impact of the maximum cross-sectional position on the envelope aeroelastic results, different maximum cross-sectional position cases are analyzed. The calculation model is the NPL envelope, and the boundary conditions are set the same as the previous section. The maximum diameter, length and volume of analyzed model are maintained constant. Defining a dimensionless parameter η as the ratio of the maximum length of the maximum cross-sectional location away from the head origin and the length of the envelope, the range of η is 0.3 to 0.6.

Envelope drag and volumetric drag coefficient along with the position of the maximum cross-section area is shown in Fig. 7. Fig. 7 indicates that there is minimum drag and volumetric drag coefficient when the value of η is 0.45. When the value of η is less than 0.45, the envelope drag and volumetric drag coefficient will decrease rapidly along with the increasing of η , when the value of η is greater than 0.45, the envelope drag and volumetric drag coefficient will increase gradually along with the increase of η.

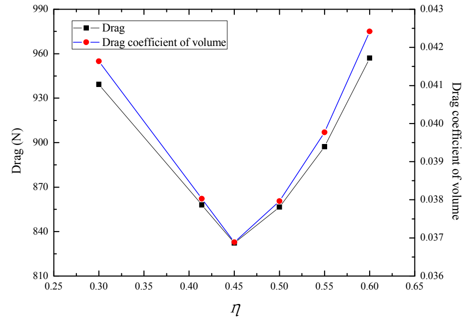

Fig.7 The drag and volumetric drag coefficient vs. position of maximum cross-section area

3.3 Influence analysis of the Reynolds number

Referring to the international standard atmospheric environmental parameters, as altitude increases, the air kinematic viscosity will gradually increase. So in case of the constant wind speed, due to the external atmospheric density gradually decreasing, the volume of the whole envelope Reynolds number will decrease.

Figure 8 shows the relational curve of the envelope drag, volumetric drag coefficient and the Reynolds number. Fig. 8 shows that, the envelope drag increases are proportionate to the increases of the Reynolds number. For volumetric drag coefficient, as the Reynolds number increases, the volumetric drag coefficient will gradually increase, and then there is a gentle process. The main reason of the flat section is that the increase proportion of envelope drag is nearly the same as the increase proportion of the atmospheric density.

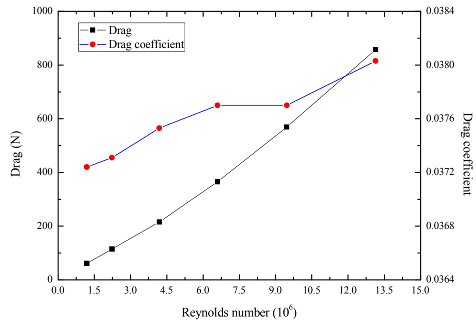

Fig.8 The envelope drag and volumetric drag coefficient vs. Reynolds number

4 CONCLUSIONS

- As to the envelope flexible characteristics, a verified method is proposed based on the ADINA software. With the proposed computational approach, the NPL envelope is analyzed. The changes of slenderness ratio, position of maximum cross-section area and Reynolds number are studied and the aeroelastic characteristics of flexible envelope are analyzed.
- Numerical results indicate that there is the minimum drag and volumetric coefficient when the value of slenderness ratio is about 5, and there is minimal drag and

volumetric drag coefficient when the value of η is 0.45, and the envelope drag increases along with the increasing of Reynolds number. The work of this paper can give some valuable information for precise forecast of the overall airship performance.

REFERENCES

[1] K.E. Omari, E. Schall, and B. Koobus, et al, Aeroelastic coupling between a low mach inviscid flow and a flexible generic airship, RR n. (2005):54-56

[2] N. Bessert, and O. Frederich. Nonlinear airship areoelasticity, *J. of Fluids and Structures*, (2005) 21:731-742

[3] ADINA. Theory and modeling guide volume Ⅲ: ADINA CFD & FSI[R]. Report ARD (2010)10-9: 238-245.

[4] Peter Funk, Thorsten Lutz, and Siegfried Wagner, Experimental investigations on hull-fin interferences of the LOTTE airship, *Aerospace Science and Technology.* (2003)**7:** 603−610

[5] Xiaojian Li, Xiande Fang, and Qiu-Ming Dai, et al. Modelling and analysis of floating performances of stratospheric semi-rigid airships. *Advances in Space Research*. (2012)50:881-890

[6] Yiran Wang and Yunxia Liu. Numerical simulation about thermal environment of solar energy airship in stratosphere. *Procedia Engineering.* (2012)29:1745-1749.

[7] Galina Ilieva, Jose C. Pascos, Antonio Dumas and Michele Trancossi. A critical review of propulsion concepts for modern airship. *Central European Journal of Engineering*. (2012)2:189-200