Contents lists available at ScienceDirect

Theoretical and Applied Mechanics Letters

Letter

Experiment and numerical simulation on the characteristics of fluid–structure interactions of non-rigid airships

CrossMark

Xiaocui Wu, Yiwei Wang *, Chenguang Huang, Yubiao Liu, Lingling Lu

Key Laboratory for Mechanics in Fluid Solid Coupling Systems, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

A B S T R A C T

Fluid–structure interaction is an important issue for non-rigid airships with inflated envelopes. In this study, a wind tunnel test is conducted, and a loosely coupled procedure is correspondingly established for numerical simulation based on computational fluid dynamics and nonlinear finite element analysis methods. The typical results of the numerical simulation and wind tunnel experiment, including the overall lift and deformation, are in good agreement with each other. The results obtained indicate that the effect of fluid–structure interaction is noticeable and should be considered for non-rigid airships. Flow-induced deformation can further intensify the upward lift force and pitching moment, which can lead to a large deformation. Under a wind speed of 15 m/s, the lift force of the non-rigid model is increased to approximately 60% compared with that of the rigid model under a high angle of attack.

© 2015 The Authors. Published by Elsevier Ltd on behalf of The Chinese Society of Theoretical and Applied Mechanics. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

As a lighter-than-air aircraft, airships are important platforms for transport and observation in the air. On the basis of their hull structure configuration, airships can be classified into three categories, namely, rigid, non-rigid, and semi-rigid airships [1]. Among all types of airships, non-rigid airships with inflated envelopes are the most common. Given that airships can be easily deformed, two aspects of fluid–structure coupling issues should be considered, i.e., the deformation of airships in flight and the influences of this deformation on the aerodynamic characteristics of airships.

Numerical simulation is the main approach for analyzing the effects of the fluid–structure interaction (FSI) of airships. Bessert [2] presented a coupling scheme based on the standard solvers of ABAQUS and VSAERO to investigate the nonlinear aeroelastic behavior of an airship (i.e., CL160). The lift curve slope of the nonlinear elastic model was noticeably larger than those of the rigid and linear elastic models. Liu [3,4] numerically investigated the aeroelasticity of a nonlinear airship with consideration of its aerodynamics and structure coupling by combining a nonlinear finite element analysis (FEA) model and a computational fluid dynamics (CFD) model. The elasticity of the airship hull exerted relatively small effects on the lift. Other works [5,6] and relevant researches on airship envelopes have considered the effects of FSI [7,8].

In their review article, Li et al. [9] comprehensively summarized the effects of FSI. They noted that they could hardly draw any

definitive conclusions about the influence and importance of airship deformation on aerodynamics because of two reasons. First, such difficulty is caused by the differences in the models from different studies and the possible variations in the accuracies of the coupling methods used. Second, the quantitative experimental data on airships with FSI are extremely limited; the same is true for wind tunnel and flight measurement tests. Furthermore, only a few qualitative observations have been made in the literature, and such observations demonstrate that airship deformation could be approximated in the form of beam bending.

In the present study, wind tunnel test measurements are performed with a typical non-rigid airship model. On the basis of CFD and nonlinear FEA methods, a loosely coupled procedure is established for the FSI of airships. The deformation characteristics of the typical conditions of an airship are analyzed, and the variations in the overall aerodynamic characteristics caused by deformation are investigated.

A wind tunnel test with a non-rigid airship is accomplished in the low-speed wind tunnel of the China Academy of Aerospace Aerodynamics with a 3 m × 3 m section (as shown in Fig. 1). The length of the airship model is 2.3 m, and its maximum diameter is 0.6 m. The arrangement of the rudders follows the Y type, and the airship is fixed on the tail in the experiment. The inflow velocity is 15 m/s, and the attack angle of the airship varies from 0° to 12°. The airship envelope is made of a polyvinyl chloride (PVC) thin film.

To obtain and compare the results, a loose coupling method is adopted in solving the FSI of the airship. The surface force is obtained by solving the Reynolds-averaged Navier–Stokes

* Corresponding author.
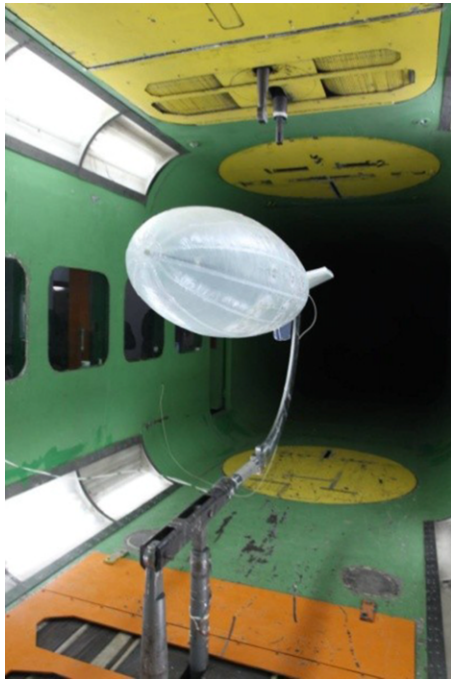   *E-mail address:* wangyw@imech.ac.cn (Y. Wang).

Fig. 1. The soft airship model wind tunnel test.

Fig. 2. The strategy of fluid–structure coupling.

equations (RANS) in the commercial software FLUENT. The shear stress transport (SST) $k - \omega$ turbulence mode and an unstructured mesh with prism-type boundary layer elements are also used. The CFD method is validated by comparing its results with the wind tunnel experimental data of the LOTTE airship. The LOTTE airship is a remote-controlled solar-powered airship, which serves both as reference configuration for theoretical investigations and as a flying test bed. More details about LOTTE can be referred to Refs. [10,11]. The CFD method is comprehensively explained in Ref. [12]. For the structure solver, the boundary displacement is obtained by using the finite element method with consideration of the large, nonlinear deformation in ANSYS. A thin plate spline interpolation scheme is adopted as the interface to facilitate the exchange of information between the fluid and structure solvers. Figure 2 shows the strategy of the fluid–structure coupling method. The results in every iterative loop are convergent for each solver. The whole coupling process is considered to be convergent if the structure deformation difference between two adjacent iterative loops is less than the criterion. For each calculation condition, the iterative loops less than 100 are needed.

Figure 3 presents a comparison of the lift coefficient curves obtained from the wind tunnel test and numerical simulation. The final result for each condition is obtained using 50 iterative loops. The computation values are in good agreement with the experimental values; the largest error is within 15%.

The lift coefficient curves in the experiments withnon-rigid and rigid models are shown in Fig. 4. In this figure, the black line represents the results obtained with the rigid model, which cannot be deformed, and the red line denotes the results obtained with the non-rigid model with consideration of FSI. For the non-rigid model, the lift force nonlinearly increases with the attack angle under a certain wind speed. When flexible deformation is considered, the slope of the lift angle of the non-rigid model is notably higher than that of the rigid model. This observation is similar to the results obtained by Bessert [2]. The lift coefficient of the non-rigid model is increased up to nearly 60% compared with that of the rigid model at a high angle of attack.

The errors observed in the wind tunnel experiments (Figs. 3 and 4) may be due to the errors of the force measurement
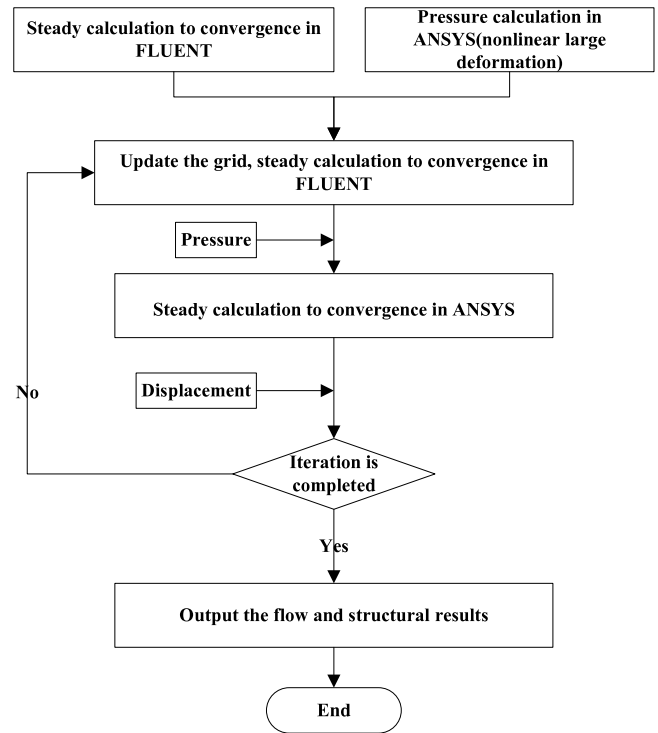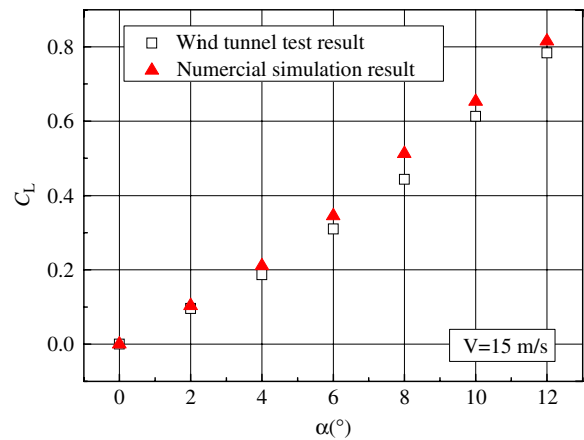

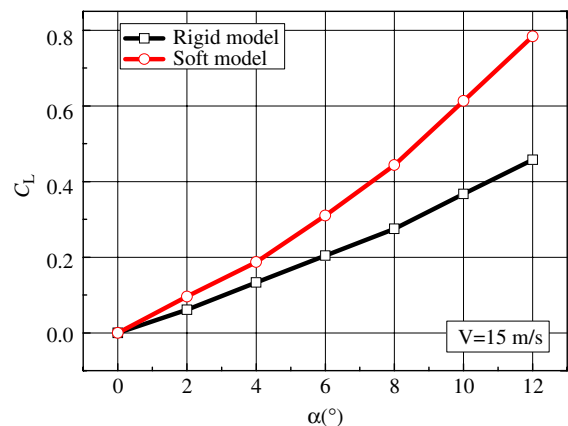Fig. 3. The lift coefficient curve of non-rigid airship model.

Fig. 4. Lift coefficient curve compared rigid model with non-rigid model in wind tunnel test. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)