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INVESTIGATION OF AIRSHIP AEROELASTICITY USING FLUID-STRUCTURE INTERACTION*

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Abstract: Due to the flexibility of the envelope of large stratosphere airships, the aerodynamic solution of such airship is closely related to its shape and the external aerodynamic forces which lead to the structural deformation. It is essentially one of the Fluid-Structure Interaction (FSI) problems. This article aims at the numerical investigation of nonlinear airship aeroelasticity in consideration of aerodynamics and structure coupling, using an iteration method. The three-dimensional flow around the airship was numerically studied by means of the SIMPLE method based on the finite volume method. Nonlinear finite element analysis was employed for geometrically nonlinear deformation of the airship shape. Comparison of aerodynamic parameters and the pressure distribution between rigid and aeroelastic models was conducted when an airship is in a trimmed flight state in specified flight conditions. The effect of aeroelasticity on the airship aerodynamics was detailed.

Key words: airship, three-dimensional flow, elastic deformation, fluid-structure interaction

1. Introduction

The design of stratosphere airships is different from other vehicles in two particular features:

(1) The airship requires large volume which provides enough buoyancy to keep it stay in the stratosphere, where the density of air is only as much as one thirteenth of that on the sea level.

(2) The light material is adopted in order to meet the demand for small weight of the airship, which results in the considerable flexibility of the whole envelope.

For such features, the flexible hull of the airship undergoes shape changes under external forces, meanwhile, the shape variations affect the pattern and structure of its surrounding fluid flow. This is a problem of static aeroelasticity. That is, load distribution occurs because the deformation of the airship influences the distribution of aerodynamic pressures over the structure. To get accurate results, the complete behavior of the airship in real flow conditions should be simulated, taking into account the hull deformation in different flowing situations. This is possible with coupled CFD and CSD simulation.

Coupled fluid-structure studies have been the subject of a large amount of development in the last two decades. Engineering applications of aeroelasticity studies are in their great majority concerned with aircraft domains. However, published aeroelastic studies about airships remain rare [1]. Wang and Shan [2] adopted a panel method to estimate the aerodynamic force of stratosphere airships. But the aeroelasticity effect had not been taken into account in their work. With the help of ABAQUS and the software VSAERO which is based on potential flow theory, Bessert and Frederich[1] investigated the influence of aerodynamics on the structural behaviour of the airship. In this paper a three-dimensional model is developed to account for the nonlinear deformation of the airship interacting with viscous flows. For a typical airship in steady flight, part of the aerodynamic drag owes its origin to the bare hull and the remaining is generated by fins, gondolas, and engines. The bare hull drag could account for about 60%-70% of the total, the proportion increasing with

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the airship size as the appendages become smaller in relation to the hull [3]. At the first stage in our study, more attention was paid to the bare hull, the envelope of the airship, which is considered as a membrane structure. The Green-Lagrange strain tensor is employed for the description of large deformation. A nonlinear finite element method was introduced for solving the structure equations of the airship. The flow solver is derived based on the Reynolds-averaged Navier-Stokes equations. A Thin Plate Spline (TPS) is adopted as the interface to exchange the information between the fluid and structure computations.

2. Mathematic model of fluid flow around airship

In this section, the fluid flow solver and the physical model of fluid dynamics are presented. The governing equations of fluid flow are the mass conservation equation and Reynolds-averaged Navier-Stokes equations. For simulating turbulent we employ the standard k-ε two model (Jones and Launder 1972) and *LL*-Low Reynolds modified model[4-6] . The unknown functions, which will be solved later, are the velocity components $\underline{u} = (u, v, w)$ in the $x-$, $y-$ and $z-$ directions, pressure p, kinetic energy of turbulence k, and dissipation ε.

The mass conservation equation and the three-dimensional Navier-Stokes equations for incompressible flow can be written as

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho U_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \rho U_j}{\partial t} + \frac{\partial U_i U_j}{\partial x_j} = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j} \bullet \left[(\mu + \mu_T) \left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i} \right) \right] \tag{2}$$

The kinetic energy equation is expressed as

$$\rho \frac{\partial k}{\partial t} + \rho U_j \frac{\partial k}{\partial x_j} = P - \rho \varepsilon + \frac{\partial}{\partial x_j} \bullet \left[(\mu + \mu_T) \frac{\partial k}{\partial x_j} \right] \tag{3}$$

The dissipation equation is

$$\rho \frac{\partial \varepsilon}{\partial t} + \rho U_j \frac{\partial \varepsilon}{\partial x_j} = f_1 C_{\varepsilon 1} \frac{\varepsilon}{k} P - f_2 C_{\varepsilon 2} P \frac{\varepsilon^2}{k} + \frac{\partial}{\partial x_j} \left[\left(\mu + \mu_T \frac{\mu_T}{Pr_z} \right) \frac{\partial \varepsilon}{\partial x_j} \right] \tag{4}$$

where

$$f_1 = 1 + \frac{P}{P^*}, \quad f_2 = 1 - 0.3\mathrm{e}^{-R_t^2},$$

$$f_\mu = \frac{1 - \mathrm{e}^{-\alpha_\mu R_k}}{1 - \mathrm{e}^{-\alpha_\varepsilon R_k}}, \quad R_t = \frac{k^2}{\nu \varepsilon},$$

$$R_k = \frac{\sqrt{k} n}{\nu}, \quad P^* = \frac{f_2 C_{\varepsilon 2} k^{1.5}}{C_{\varepsilon 1} L_\varepsilon} \mathrm{e}^{-\alpha_d R_k^2},$$

$$L_\varepsilon = \kappa c_\mu^{0.75} n (1 - \mathrm{e}^{-\alpha_\varepsilon R_k}), \quad C_{\varepsilon 1} = 1.44,$$

$$C_{\varepsilon 2} = 1.92, \quad Pr_k = 1, \quad Pr_\varepsilon = 1.3,$$

$$\alpha_d = 0.0022, \quad \alpha_\varepsilon = 0.263, \quad \alpha_\mu = 0.016$$

The coefficient of eddy viscosity μ_T is defined by

$$\mu_T = \rho f_\mu c_\mu \frac{k^2}{\varepsilon} \tag{5}$$

To solve the equations of fluid flow, proper boundary conditions are required. At the inlet boundary, the inflow velocity is given. At the outlet boundary, extrapolation of the velocity, kinetic energy of turbulence and dissipation to the boundary (zero gradient) can usually be used for steady flows when the outflow boundary is far from the region of interest. At the interface between fluid and airship surface, the non-slip condition is applied.

3. Numerical solver for fluid flow and airship structure

The basic method of fluid simulation is pressure correction method and the finite volume is used for numerical discretization[7, 8].

The computational code is programmed by the authors. The validity of the results from this program has been evaluated against different kinds of velocities from incompressible flow to transonic flow and